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BRLCB: A Closed-Chamber Data Analysis Program Part I—Theory and User's Manual

William F. Oberle
Douglas E. Kooker

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13. ABSTRACT *(Maximum 200 words)*

BRLCB is a PC-based analysis program designed to perform all data analysis associated with closed-chamber experiments. Included in the program are provisions for deterred and layered propellants and electrothermal-chemical augmented firings. The basic features of the program and user's guide are presented and validated, and future plans and additions to the program are outlined.

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1. INTRODUCTION

BRLCB is a comprehensive closed-chamber data analysis program designed to perform all analysis associated with the high-pressure combustion research facility located at the Weapons Technology Directorate, U.S. Army Research Laboratory (ARL). The program offers five different analysis modes. First, the traditional burn rate analysis which determines the apparent linear burning or regression rate for a propellant given an experimental closed-chamber pressure history together with the propellant thermochemistry and geometry. Second, a synthetic pressure-time generation mode which calculates the expected closed-chamber pressure-time profile given propellant thermochemistry, linear burn rate, and geometry. The third analysis mode is determination of propellant surface area. This analysis determines the reacting (burning) surface area of the propellant required to support the experimental pressure-time profile given propellant thermochemistry, geometry, and linear burning rate. Analysis mode 4 is referred to as an interrupted chamber analysis which is identical to the burn rate analysis except that the pressure-time profile is for incomplete (interrupted) propellant burning which results when a "blow-out disc" in the closed vessel ruptures at a predefined pressure and terminates propellant combustion. The fifth and final mode of analysis is also a burn rate analysis, but is for the analysis of propellant burning coupled with the injection of an electrically generated plasma into the closed chamber. This mode is specifically designed for investigation of potential propellants for use in electrothermal-chemical (ETC) gun applications. In addition to the five analysis modes, the program includes extensive provisions for data preparation (smoothing, etc.), graphics capabilities, and post-processing for preparation of output.

Over the years, a number of programs have been developed to perform both the burn rate and surface area analysis (Robbins and Horst 1976; Price and Juhasz 1977; Oberle, Juhasz, and Griffie 1987; Oberle and Kooker 1989). However, except for the Oberle and Kooker program, these programs were designed to accommodate only homogenous propellants (i.e., propellants with constant thermochemical properties). An important feature of BRLCB is the ability to analyze not only homogeneous propellant burning but also layered and deterred propellant burning.

The principal objective of this report is to provide details for using the various program options and analysis modes. In addition, the report provides details of the theory underlying the different analysis modes, results of test cases utilized in verifying and testing the computer program implementation of the model, and, finally, comparison with results obtained using other closed-chamber data analysis programs. To accomplish this objective, this report is divided into four main sections: (1) User's Guide and Program

Description, (2) Theoretical Analysis of Closed-Chamber Combustion, (3) Validation, and (4) Comparison With Other Closed-Chamber Data Reduction Programs.

2. USER'S GUIDE AND PROGRAM DESCRIPTION

2.1 Program Structure and Overview. BRLCB is intended for use on an IBM PC or compatible. However, the program is written in standard FORTRAN 77 and can be ported to operate on any system which supports FORTRAN, the exceptions being the graphics routines utilized in the program. In actuality, the BRLCB program structure is not that of single large program but of 8 individual FORTRAN programs, 1 DOS batch file program, and 34 ancillary information files which are listed in Table 1. (Note: To run BRLCB, all of the files listed below should be contained in a separate directory, preferably on a hard disk. In this report, it will be assumed that all the files are in a separate directory with the user logged into that directory.)

Table 1. Required FORTRAN, DOS Batch, and Ancillary Files for BRLCB

FORTRAN Programs		
MKCHCE.EXE	MKMASTER.EXE	MKGAGE.EXE
MKPTDATA.EXE	MKINF.EXE	MKSMOOTH.EXE
MKCAL.EXE	MKOUT.EXE	
DOS Batch File		
BRL.BAT		
Ancillary Files		
IGNITER.INF	GAGEFILE	
S5.CFF	D5.CFF	
S7 CFF	D7.CFF	
S9.CFF	D9.CFF	
S11.CFF	D11.CFF	
S13.CFF	D13.CFF	
S15.CFF	D15.CFF	
S17.CFF	D17.CFF	
S19.CFF	D19.CFF	
S21.CFF	D21.CFF	
S23.CFF	D23.CFF	
S25.CFF	D25.CFF	
S27.CFF	D27.CFF	
S29.CFF	D29.CFF	
S31.CFF	D31.CFF	
S33.CFF	D33.CFF	
S35.CFF	D35.CFF	

A complete listing of all the programs and files are found in Appendices D–L. A brief description of each program or file is provided below.

MKCHCE.EXE	:	Overall controller program for BRLCB which allows program options to be invoked from a menu.
MKMASTER.EXE	:	Program used to create master information file to be used in the data analysis.
MKGAGE.EXE	:	Program used to maintain pressure transducer calibration information file which is used if voltage-time data must be converted to pressure-time data.
MKPTDATA.EXE	:	Program used to import experimental data into BRLCB.
MKINF.EXE	:	Program used to update a master information file created in program MKMASTER.EXE for a specific closed-chamber experiment.
MKSMOOTH.EXE	:	Program used to prepare the pressure-time data for the analysis.
MKCAL.EXE	:	Program which performs the selected data analysis.
MKOUT.EXE	:	Program which provides both paper and disk output of the program results.
BRL.BAT	:	DOS batch file used with MKCHCE.EXE to control program flow.
IGNITER.INF	:	Data file which stores thermochemical properties of various igniters.
GAGEFILE	:	Data file which stores pressure transducer calibration information.
S5.CFF—S35.CFF	:	Data files containing the numerical coefficients utilized in smoothing the pressure-time data.
D5.CFF—D35.CFF	:	Data files containing the numerical coefficients utilized in differentiating the pressure-time data.

The remainder of this section will cover running the program and options which must be run for the different analysis modes. Subsequent sections will provide additional details on the seven main programs which comprise BRLCB.

To begin BRLCB, at the DOS prompt type BRL. This will invoke the batch file listed above, which after some initialization will call the program MKCHCE.EXE. The main BRLCB menu (see Table 2) will then be displayed.

Table 2. Main Menu for BRLCB

BRLCB ** Version 3.0 ** January 1992
Main Menu
1. Create Master Information File 2. Update gage information 3. Prepare pressure-time data 4. Prepare firing information file 5. Smooth pressure-time data 6. Perform data analysis 7. Prepare output 8. Exit
Please enter your choice (1–8).

The particular sequence of options to select will depend upon the analysis mode desired. Figures 1 and 2 illustrate the option flow for the five analysis modes. The options must be performed in the indicated order if the program is to work correctly, and all options indicated must be selected.* Appendix A lists the information required by the user for each option.

*Option 1. Create master information file, does not have to be invoked if an appropriate master file for the analysis already exists.

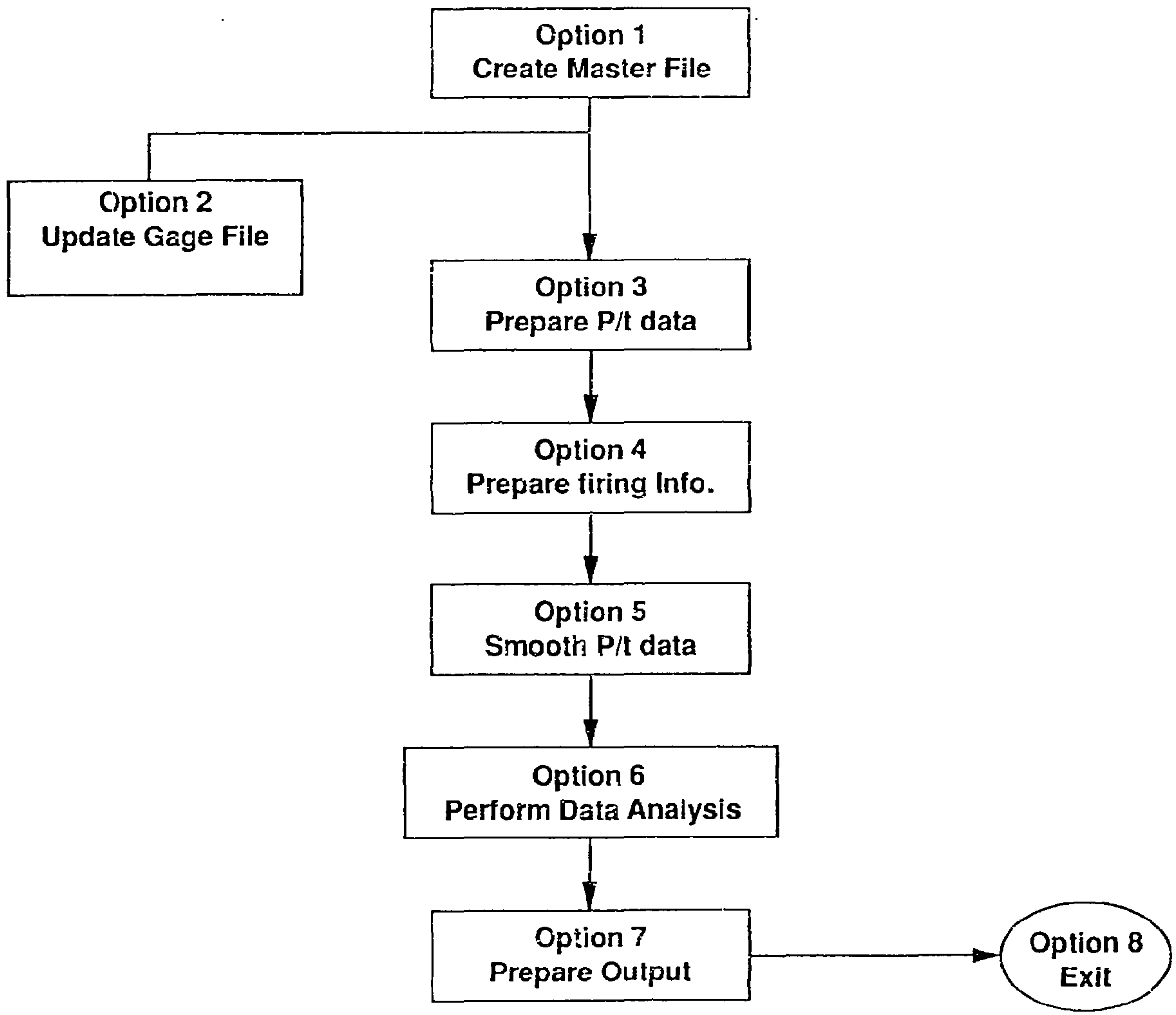

Figure 1. Option flow for analysis dodes: (1) burn rate reduction; (3) surface area analysis; (4) interrupted burner; and (5) ETC burn rate reduction.

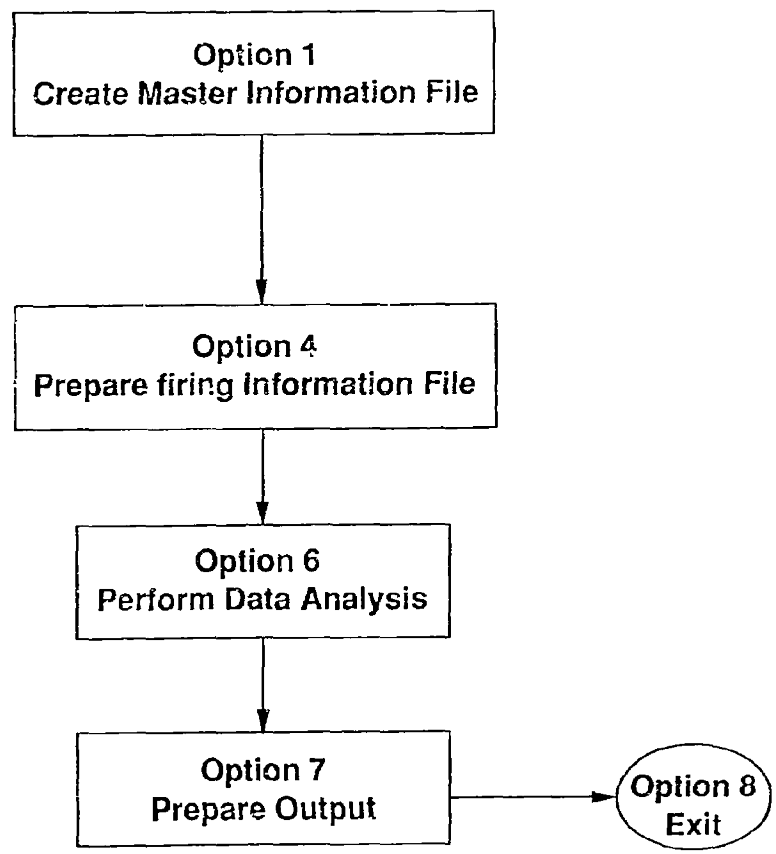

Figure 2. Option flow for analysis mode (2) generate pressure-time data.

2.2 Option 1, Create Master Information File (Program MKMASTER.EXE). In BRLCB, the master information file is the starting point regardless of the analysis mode. The idea behind the master information file (.MAS suggested file extension) is that certain information (e.g., propellant geometry) will remain fixed for several experimental firings. Thus, one master file will be created which will then be utilized to create an updated file (referred to as the .INF in Option 4, Preparing Firing Information file). The .INF file will contain information specific (e.g., propellant mass) to a single experimental firing.

Figure 3 provides an outline of the information required in Option 1.

MAKMASTER.EXE

- *Identification Information*
- *Propellant Information*
  - **A. Identification**
  - **B. Thermochemistry**
    - **1. Number of Layers**
    - **2. Constant Properties vs. Varying Properties**
      - **Flame Temperature (K)**
      - **Impetus (J / g)**
      - **Molecular Weight**
      - **Covolume (cc / g)**
      - **Ratio of Specific Heat (-)**
      - **Density (g / cc)**
  - **C. Propellant Geometry**
- *Igniter Information*
- *Write Master File (.MAS suggested file extension)*
- *Exit*

Figure 3. Overview of information required in Option 1.

Table 3 displays the first screen presented when Option 1 is run. As shown in the figure, the master information file can be created from an existing master information file. However, this capability is very limited—editing single entries of an existing master information file –is not available nor can the information contained in the previous master information file be previewed. In building from an existing file, it is assumed that the user is cognizant of the contents of the previous master information file and

Table 3. Option 1, Screen 1

BRLCB ** Version 3.0 ** January 1992
Creating a Master Infomation file
This program will create a master information file which will contain information that does not change from one firing to the next. Create .MAS file from existing file? [Y/N] Default: Y

will use the file to avoid re-entering certain blocks of information (generally, thermochemistry or geometry under propellant information, Figure 3). It is recommended that master information files be created from the beginning until the user becomes very familiar with the overall BRLCB program structure. The structure of master information and .INF (created in Option 4) files is provided in Appendix B. These files are saved as ASCII files and could be directly edited with any standard word processor, bypassing Options 1 and 4 altogether. However, care must be taken in editing these files since all subsequent file names (automatically generated by the program) utilized in the analysis are stored in these files. Failure to correctly modify any of the stored file names will result in loss of data. Direct editing of the master information or .INF file is not recommended.

2.2.1 Identification Information. After selecting whether or not to create the master information file from an existing file, the identification information (Figure 3) suboption is automatically selected. It is in this suboption that the file name associated with the master information file being created is requested. Although any acceptable DOS name and extension can be used, ***IT IS RECOMMENDED THAT ALL MASTER INFORMATION FILES HAVE AN EXTENSION OF .MAS***. Once the identification information is completed, the user is returned to the main menu, as shown in Table 4.

2.2.2 Propellant Information - Identification. As shown in Figure 3, the propellant information suboption has three parts—identification, thermochemistry, and geometry. Identification requests information concerning the propellant type, source, and lot. A complete understanding of the information requested and the choices made in the thermochemistry and geometry sections of the propellant information suboption are required for effective use of BRLCB. A detailed description for these sections is provided in the next two sections of this report.

Table 4. Main Menu for Option 1

Creation of Master File: Main Menu	
1.	Identification information *
2.	Propellant information
3.	Igniter information
4.	Write the master file
5.	Exit
An * indicates that the information has been provided. Please enter your choice (1–5).	

(1) Propellant Information - Thermochemistry. In this portion of the program, thermochemical properties associated with a single grain are supplied to the program. BRLCB makes no distinction between homogeneous (single layer with constant thermochemical properties), layered (several layers with each layer having constant thermochemical properties), and deterred (continuously varying thermochemical properties in at least one layer) propellant grains. However, the required computational time for homogeneous and layered propellants is several orders of magnitude faster than for variable thermochemical properties, as shown in Table 5, where a five-layer sphere with constant properties in each layer is analyzed as a layered propellant and then as a deterred propellant. Thus, whenever possible, deterred propellants should be described as a multilayered propellant. Describing a propellant as consisting of 15 layers with constant thermochemical properties in each layer will result in a substantially faster run time than describing the propellant grain as a single layer with continuously varying thermochemical properties.

Table 5. Run Times on CRAY XMP for Five-Layer Sphere, Constant Thermochemical Properties in Each Layer

Method	CPU Time (s)
Layered	0.206
Deterred	31.6

The first information requested under the thermochemistry section is for the number of layers in the grain. The grain can have up to 15 layers. If the number of layers is greater than one, the user is prompted to enter the starting depth of each layer, as shown in Table 6. Note from Table 6 that grain slivering should only occur in the inner most layer of the grain. However, BRLCB will still correctly perform the desired analysis if grain slivering occurs in a layer besides the innermost layer. The authors feel that determination of layer depths and changing thermochemical properties when slivering occurs (in actual propellant grains) will be very inaccurate.

Table 6. Prompt for Starting Depth of Each Layer

Enter the starting depth for each layer. The first layer starts at a depth of 0 cm and will be automatically entered. The last layer must start at a depth no deeper that one-half the length of the smallest web (i.e., no slivering may occur except in the inner layer of the grain).

To illustrate how BRLCB interprets layer starting depth, consider Figures 4 and 5. Figure 4 is to represent propellant grains which have no perforations or slots (in this case, a spherical grain of radius 9 cm consisting of three layers). Layer 1 is always the outside layer and starts at a depth of 0.0 cm. Successively numbered layers proceed into the grain with the highest numbered layer being the innermost layer. As shown in Figure 4, the starting depth for layer two is 4.0 cm and for layer three, 7.0 cm. Figure 5 is to represent propellant grains with perforations. Specifically, Figure 5 shows the end view of a single, perforated grain with three layers. Note that layers 1 and 2 form two distinct regions into the grain. Layer 1 is the layer adjacent to the propellant grain boundary (in this case, the perforation boundary and outer boundary), while layer 3 is the innermost layer. Layer 1 starts at a depth of 0.0 cm, layer 2 at 1.5 cm, and layer 3 at 2.5 cm.

After the number of layers and starting depth of each layer is entered, the user is prompted to enter whether the layers will all have constant thermochemical properties or whether at least one layer will have continuously varying properties. If all layers have constant thermochemical properties, the values for the properties listed in Table 7 will be requested for each layer.

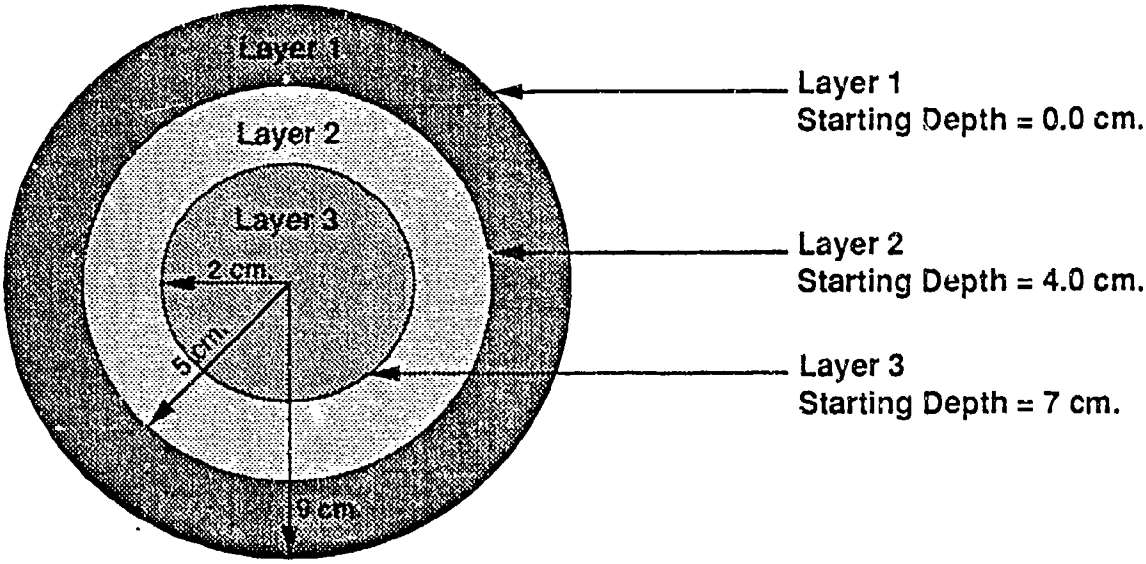

Figure 4. Starting depths for layers of a grain without perforation or slots.

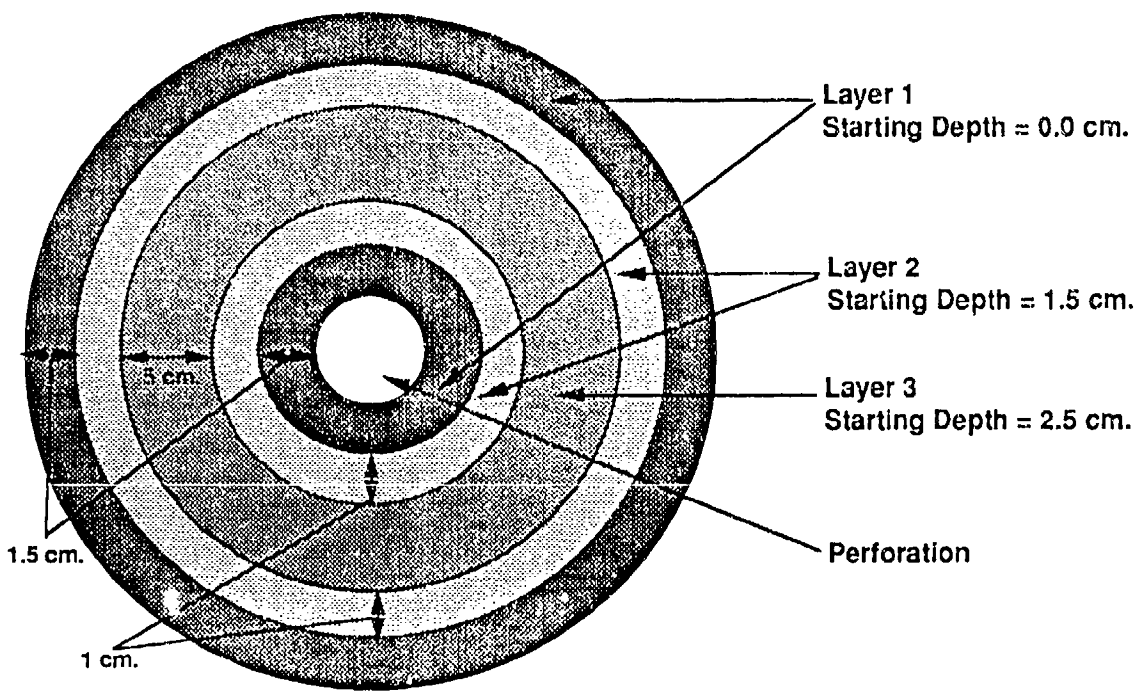

Figure 5. Starting depths for grains with perforations.

Table 7. Required Thermochemical Properties

Property	Units
Flame temperature	K
Impetus	J/g
Molecular weight	–
Covolume	cm^3/g
Ratio of specific heats	–
Density	g/cm^3

A value for molecular weight consistent with the flame temperature and impetus will be suggested by the program. This value should be accepted, it is the flame temperature and molecular weight which is used in the analysis, not the impetus. The molecular weight is computed from the flame temperature and impetus by the following equation

$$\text{Molecular Weight} = \frac{8.314 * \text{Flame Temperature}}{\text{Impetus}} \quad . \tag{1}$$

If any layer has continuously varying properties, the user will be prompted (see Table 8) to enter the thermochemical properties shown in Table 7 at both the beginning and end of each layer. The molecular weight, in this case, is not computed by the program; the user must determine a consistent value with flame temperature and impetus for the molecular weight. Equation (1) can be utilized for this purpose.

Table 8. Prompt for Entering Continuously Varying Thermochemical Properties

Values will be entered for the beginning and end of each layer. All input in metric units. For any layer, there should be no more than a 20% variation in any property.

(2) Propellant Information - Geometry: Currently, BRLCB supports 13 grain geometrics, as shown in Table 9.

Table 9. Grain Geometries Supported by BRLCB

1.	Sphere
2.	Cord
3.	Rectangular strip
4.	1-Perforated cylinder
5.	Slotted tube
6.	7-Perforation cylinder
7.	7-Perforation hexagonal
8.	19-Perforation cylinder
9.	19-Perforation hexagonal
10.	37-Perforation hexagonal
11.	Cord with inhibited ends
12.	Sandwich with inhibited sides
13.	Cigarette

Implementation of the first 10 grain geometries is identical to that found in the interior ballistic code IBHVG2 (Anderson and Fickie 1987). Figures 6–18 show each of the grain geometries. (Figures 6–15 are from the Anderson and Fickie report.) All perforations on a grain are assumed to have the same diameter. For hexagonal grains, the inner and middle webs must be equal. The following notation is used in the diagrams.

D	: Grain diameter	WI	: Inner web
L	: Grain length	WM	: Middle web
DP	: Perforation diameter	WO	: Outer web

Once the propellant grain dimensions are entered by the user, the program will determine if the dimensions are consistent. If not, the program will provide the user with a consistent set of dimensions. The user has the option to accept the consistent set or keep the dimensions entered. *However, for computational purposes, the dimensions must be consistent and the program will utilize the consistent set of dimensions suggested to the user in the computation even if the user elected to keep the inconsistent dimensions.*

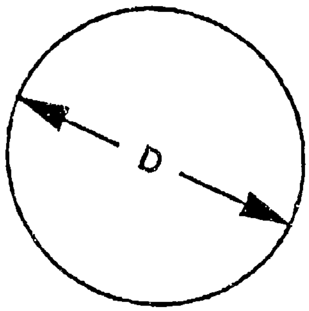

Figure 6. Sphere.

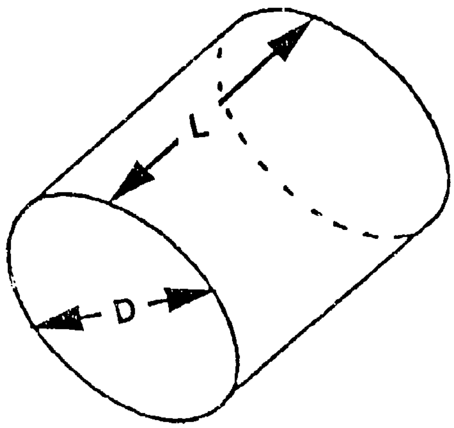

Figure 7. Cord.

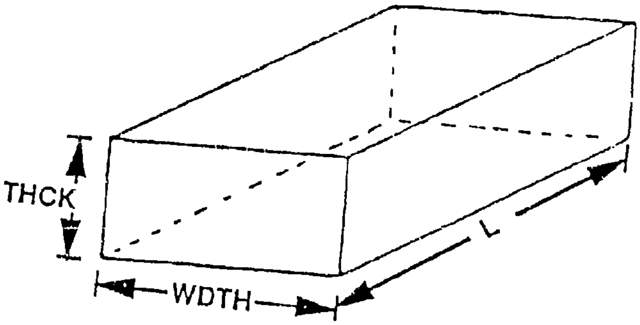

Figure 8. Rectangular Strip.

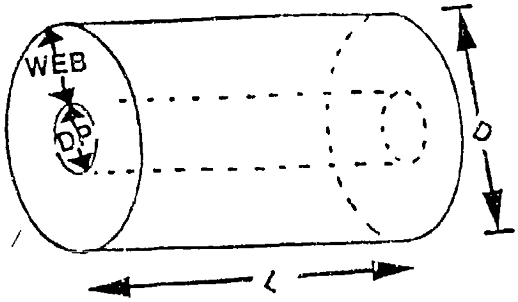

Figure 9. 1-Perforated Cylinder.

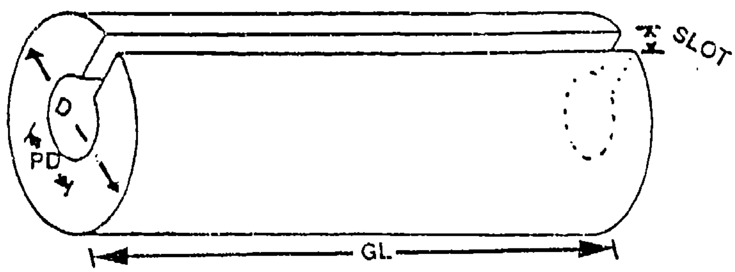

Figure 10. Slotted Tube.

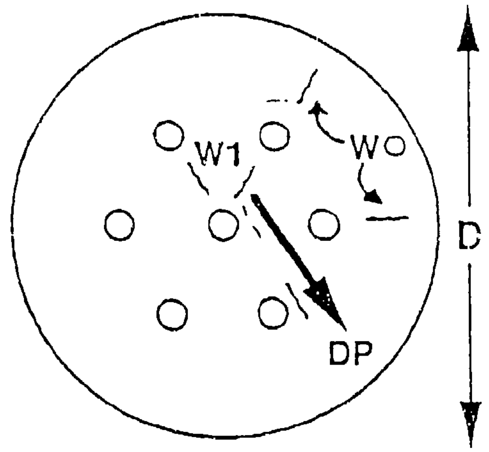

Figure 11. 7-Perforation Cylinder.

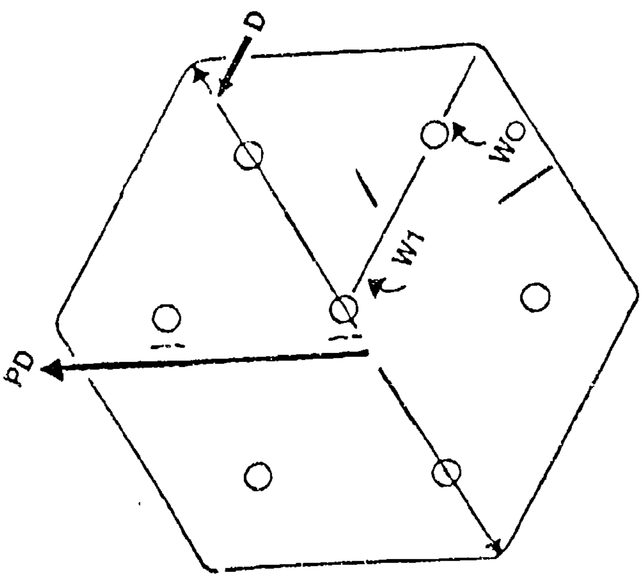

Figure 12. 7-Perforation Hexagonal.

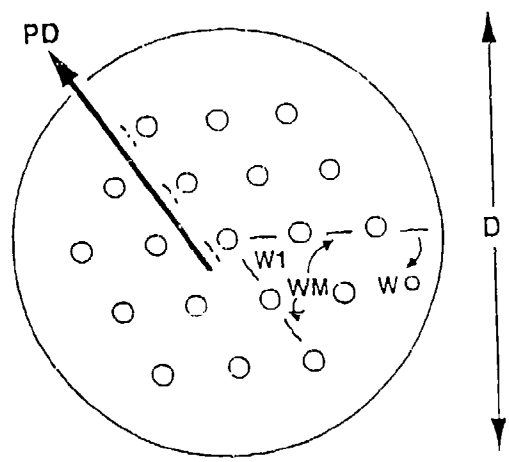

Figure 13. 19-Perforation Cylinder.

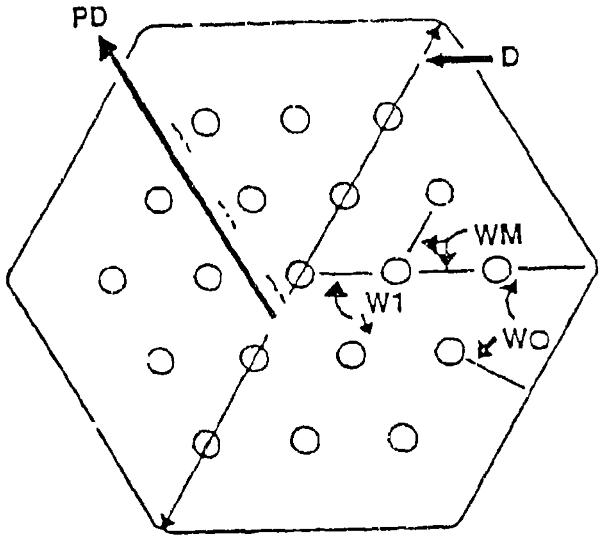

Figure 14. 19-Perforation Hexagonal.

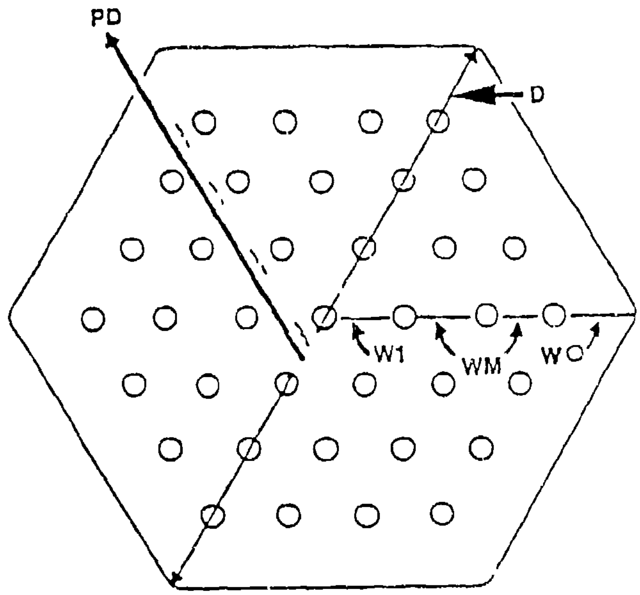

Figure 15. 37-Perforation Hexagonal.

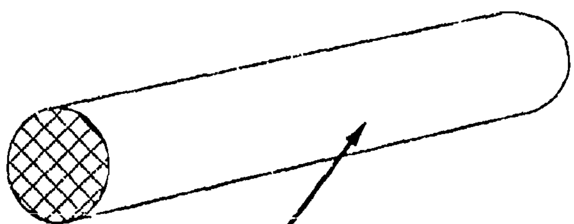

Figure 16. Cord With Inhibited Ends.

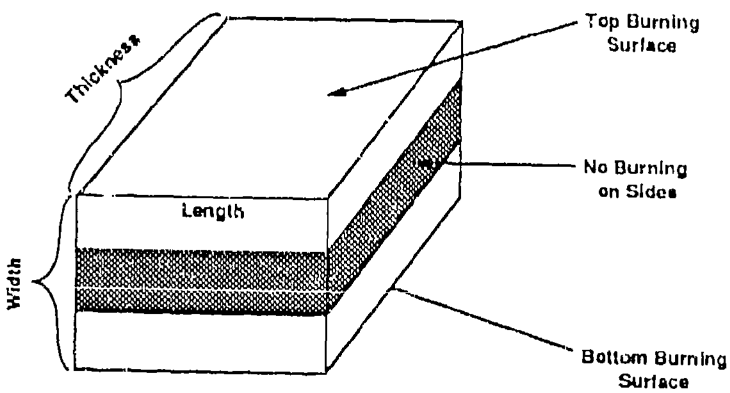

Figure 17. Sandwich With Inhibited Sides.

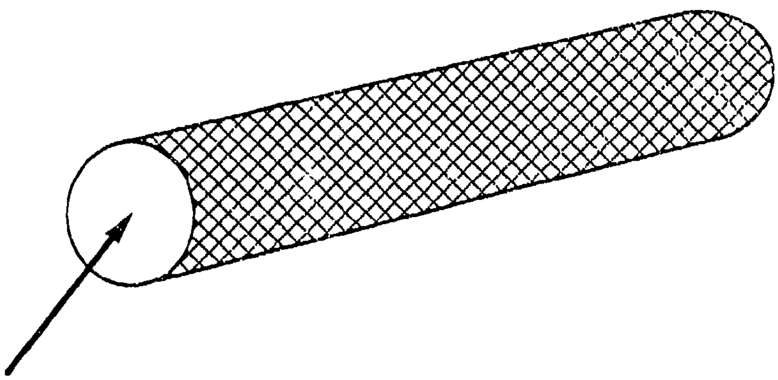

Figure 18. Cigarette.

2.2.3 Igniter Information. Three options for igniter information are provided by BRLCB, as shown in Table 10.

Table 10. BRLCB Igniter Options

Creation of Master File: Igniter Information
Information concerning the type of igniter being used is needed. The available options are:
1. Black powder 2. Enter new information 3. Use igniter library 4. Exit
Please enter your choice.

Option 1, Black Powder, sets the igniter to black powder with thermochemical properties shown in Table 11. Selecting "Enter New Information" will require the user to enter the same thermochemical values as for the propellant shown in Table 7. "Using Igniter Library" accesses the igniter information file where information on various igniters has been saved. (Note: The information in the igniter information file is built up by the user.)

Table 11. Thermochemical Properties of Black Powder Utilized in BRLCB

Theo. impetus (J/g):	290.00000
Flame temperature (K):	2188.00000
Density (g/cm^3):	1.75000
Average molecular weight:	66.37000
Covolume (cm^3/g):	0.78500
Gamma:	1.21840

After the igniter information is entered, the program returns to the main menu, Table 4, Option 4, Write Master File should then be selected. [Note: To preview the thermochemical properties entered prior to writing the Master File, enter a 10 for your selection.]

2.3 Option 2, Update Gage Information (Program MKGAGE.EXE). Generally, closed-chamber pressure transducers record "counts" or voltage which must be converted to units of pressure, which for this program must be megapascals (MPa). BRLCB permits data to be imported to the program either in units of pressure, voltage units (or any units which can be converted to pressure), or in a format specific to BRL (details provided in section on Option 3, Prepare Pressure-Time Data). However, since each research facility will have their own standard operating procedure for data acquisition, only the simplest (except for the BRL procedure) voltage-to-pressure conversion is provided in BRLCB. This conversion is based upon a second-order relation between voltage and pressure. The conversion is given by

$$\text{Pressure (MPa)} = A + Bx + Cx^2 \quad , \qquad (2)$$

where x is whatever quantity the user is employing to import the data. The coefficients A, B, and C will depend upon the units of the quantity x. However, the pressure must have units of megapascals.

The purpose of Option 2, Figure 1, is to provide a utility by which the user can maintain a data file of the conversion coefficients A, B, and C, which at the Weapons Technology Directorate, ARL, are related to the pressure gages. This data file can then be accessed in Option 3 (Prepare Pressure-Time

Data) when the data are imported to BRLCB. Using this data file will minimize the number of times the coefficients must be entered into the program if the same coefficients will be used for several data sets. Maintenance options available for manipulating the gage file are presented in Table 12. These same options are also accessible in Option 3 (Prepare Pressure-Time Data).

Table 12. Gage Maintenance Options

Gage Maintenance Program Sub Menu
1. View gage information 2. Add a gage to data base 3. Delete a gage from data base 4. Locate specific gage in data base 5. Exit
Please enter your choice (1–5).

2.4 Option 3, Prepare Pressure-Time Data (Program MKPTDATA.EXE). As indicated in the previous section, BRLCB provides five methods by which data can be imported to the program. These five methods are shown in Table 13.

Table 13. Methods by Which Data Can Be Imported to BRLCB

BRLCB supports five options for preparing the pressure-time data for the computation.
1. ASCII file of time and pressure (two columns, time/pressure) 2. ASCII file of pressure (one column, pressure) 3. ASCII file of time and voltage (two columns, time/voltage) 4. ASCII file of voltage (one column, voltage) 5. A voltage-time file from VuPoint/BRL procedure 6. Exit option
How will the pressure-time data be entered? Please enter your choice (1–5 or 6 to EXIT).

After the method by which the data will be imported to the program is selected, the file name for the data is requested. This will be followed by a prompt for the file name under which the converted data will be saved. The prompt is shown in Table 14. As stated in the prompt (Table 14), the file is to have no extension (for example, a:test1, an extension of .pvt will be automatically appended by the program to create the file a:test1.pvt). The format of the .pvt file is shown in Table 15. This file name, in the example a:test1, will be the file name used with different extensions (see Section 2.5, Option 4) for all the files created during the analysis. *IN ALL SUBSEQUENT PROGRAM OPTIONS WHEN A FILE NAME IS REQUESTED, THIS FILE NAME (WITHOUT EXTENSION) SHOULD BE USED. THE ONLY EXCEPTION BEING THE MASTER FILE NAME REQUEST IN OPTION 4.*

Table 14. File Name Prompt

Enter the file for the output file which will contain the pressure-time data ready for BRLCB. Enter file name, all DOS path conventions apply, but there can be no extension for the file. Note: This file name will be the name used for all other files produced by the BRLCB analysis. This is the file name to use when asked in subsequent options for a file name.

Table 15. Format of .PVT File

Line 1:	Number of data points
Line 2:	Maximum pressure (MPa)
Line 3:	Minimum pressure (MPa)
Line 4:	Ending time (s)
Line 5:	Starting time (0.0 s)
Line 6:	5 + number of data points = N: Col 1: time(s), Col 2: pressure (MPa)
Line N+1:	Gage ID ("none" if no gage used)
Line N+2:	Voltage input to gage (0.0 if no gage used)
Line N+3:	Constant coefficient (0.0 if no gage used)
Line N+4:	Linear coefficient (0.0 if no gage used)
Line N+5:	Second-order coefficient (0.0 if no gage used)

Once the file names have been entered, a message describing the format of the imported data file is provided. (Note: For method 5, a voltage-time file from VuPoint/BRL Procedure, see Section 2.4.1). For all other methods of importing data, the total number of data points cannot exceed 2,048 points. Next, the time step utilized in the data recording is requested. This time step is to be given in milliseconds (ms) and the data must have been recorded with this constant time step. *The burning rate and surface area analysis are predicated upon a constant time step for the data recording. This program is not designed to analyze data with unequal time steps.*

If the imported data are already in pressure units, the output file will be written and the option will be completed. For imported data in voltage (or any other units), conversion coefficients for a second-degree relation will be requested. These coefficients can be entered directly into the program or the gage file (see section 2.3) can be accessed to obtain the coefficients. Provisions for saving newly entered coefficients into the gage file are provided. Once the coefficients are entered, the output file will be written and the option will be completed.

2.4.1 VuPoint/BRL Procedure. This method is based upon the data recording procedure utilized at the Weapons Technology Directorate, ARL. Data are recorded on Nicolet oscilloscopes and then processed using the program VuPoint (S-Cubed Inc., Division of Maxwell, San Diego, CA). The VuPoint program produces two files—one containing calibration information and the second the firing data. Under this method of importing data to BRLCB, these two files, which are in units of voltage and time, are automatically read and the data converted to pressure data utilizing the method described below.

Conversion to Engineering Units.

(1) To convert the Nicolet voltage data to engineering units, the first step is to compute the response factor for the whole electronic/digital data acquisition system (i.e., the amount of charge [Q] represented by each ADC count). This is done as follows:

(a) Compute charge for calibration step

$$Q = CV_i \quad , \tag{3}$$

where

V_i = calibration voltage input to the charge amplifier*

C = capacitance of cal capacitor in charge amplifier (1,000 pF)

Q = charge, picocoulombs

*Note: The V_i information does NOT appear on the Nicolet.

(b) Charge per ADC count

$$F = Q/\left(C_{mx} - C_{mn}\right) \ , \tag{4}$$

where

F = response factor for system (picocoulombs/count)

Q = charge (picocoulombs)

C_{mx} = maximum value of cal step

C_{mn} = minimum value of cal step

Note: C_{mx} must be positive and C_{mn} negative.

(2) Converting Data to Engineering Units.

(a) The value of C_{mn} is subtracted from each pressure count. This amounts to a baseline correction to get a corrected ADC count (C_{cor}) for the pressure at each point.

(b) Using the second-order fit equation giving pressure in terms of charge developed; the pressure is computed for each time step, as indicated below:

$$P = A + B\left(FC_{cor}\right) + C\left(F\ C_{cor}\right)^2 \ , \tag{5}$$

where

P = pressure (MPa)

A, B, C = zero, first- and second-degree calibration coefficients

F = response factor (picocoulombs per ADC count)

C_{cor} = counts for each press point

2.5 Option 4, Prepare Firing Information File (Program MKINF.EXE). In Option 1, Create Master Information File, information which would remain constant for a series of experimental firings or simulations was entered and saved in a file termed the master information file. In this option (Option 4), that information specific to a single experimental firing or simulation is appended to the master information file to create a unique file known as the .INF file or information file. Since the information file is created from a master information file created in Option 1, the first query posed to the user, after

Option 4 is selected, is for the name of the master information file, as shown in Table 16. The master information file name should be given with both the drive and extension.

Tabie 16. Request for Master Information File

Information pertaining to an individual firing is entered using this option. The file is built from a master file created using Option 1. Enter the name of the master file which will be used in creating the current information file, include drive and extension.

Next, as shown in Table 17, the type of computation to be performed is determined. Depending on the computation mode selected, additional information required for the specific computation will be requested. Specific details for each computational mode are provided in the following sections.

Table 17. Prompt for Selection of Computational Mode

Enter the type of computation which is to be performed.	
1.	Burn rate reduction
2.	Inverse analysis (generate P/T)
3.	Surface area analysis
4.	Interrupted burner
5.	ETC reduction

2.5.1 Burn Rate Reduction. To perform a burning rate reduction an experimental pressure-time file is required. This file MUST be created under Option 3 before Option 4 can be selected. Thus, when the burn rate reduction mode is selected, the first request is for the name of the pressure-time file created in Option 3. This prompt is shown in Table 18. After the pressure-time file is examined, the user is asked to verify the time step.

Table 18. Prompt for Pressure-Time File Created in Option 3

Enter the name of the pressure-time file created in Option 3 which is associated with the information file being created. This file must be created before the information file is created. If the pressure-time file does not exist, exit the program and complete Option 3. Remember the file name is given without extension but all DOS path options are applicable.

As described in the section on Option 3, the name of the pressure-time file (without extension) will determine the names of all other files used in the computation. The various files and associated names (the name consists of the pressure-time file name with a specific extension) are shown in Table 19 as they are presented to the user while running Option 4. A description of each file is also provided. (Note: In Table 19, a:test1 is the example test name used in Option 3, this portion of the file names will be whatever name was used for the pressure-time file created in Option 3.)

Table 19. Files and File Names Utilized in Burn Rate Reduction

The following file names will be used:			
Master File	:	a:test1.mas	Created in Option 1
Information File	:	a:test1.inf	Created now in Option 4
Pressure-Time File	:	a:test1.pvt	Created in Option 3
Smoothed Data File	:	a:test1.pdt	Created in Option 5
Output File	:	a:test1.out	Created in Option 6
Graphics File	:	a:test1.dat	Created in Option 6
Burn Rate File	:	a:test1.br	Created in Option 6
Pause - Please enter a blank line (to continue) or a DOS command.			

Master File (filename1.mas): File created in Option 1 used to generate the information file currently being created.

Information File (filename.inf): File currently being created.

Pressure-Time File (filename.pvt): Pressure-time data file created in Option 3 associated with the information file being created.

Smoothed Data File (filename.pdt): File created in Option 5 which will contain the pressure-time data, which may be smoothed, etc., directly used in the burn rate computation.

Output File (filename.out): File to which the results of the computation will be printed.

Graphics File (filename.dat): Special file created to use with graphic packages external to the BRLCB program. The structure of this file for all the computation modes is shown in Table 20.

Table 20. Structure of Graphics File

Computational Option	Column 1	Column 2	Column 3
Burn rate reduction	Pressure (MPa)	Burn rate (cm/s)	0.0
Inverse analysis	Time (ms)	Pressure (MPa)	0.0
Surface area	Fraction burned (–)	Surface area ratio (–)	Depth burned (cm)
Interrupted burner	Pressure (MPa)	Burn rate (c/s)	0.0
ETC reduction	Pressure (MPa)	Burn rate (c/s)	0.0

Burn Rate File (filename.br): File containing results of the computation of burn rate laws in the standard $r = bP^n$ form, r in cm/s.

After the file names are determined, the specific information concerning the hardware and charge mass utilized in the experiment are requested. The necessary information, together with proper units, is presented in Table 21.

Table 21. Hardware and Charge Information Requested in Option 4

Information	Units
Bomb volume	cm^3
Initial bomb temperature	K
Propellant mass	g
Igniter mass	g
Propellant temperature	K
Igniter temperature	K

Finally, information concerning the pressure range for the burn rate laws is requested (Table 22). Pressure ranges are based upon the maximum observed pressure.

This completes the required information for the burn rate reduction analysis, the information file is then written and the program returns to the main BRLCB menu.

Table 22. Request for Pressure Ranges for Burn Rate Laws

One output of the burn rate analysis is a series of bP^n burn rate laws. The program has the option to determine the burn rate laws for any given pressure range up to the maximum pressure for the firing.
Three preset ranges can be used: 5–10% 10–25% 25–75%
1. Use predetermined ranges. 2. Enter new ranges.
Please enter your choice.

2.5.2 Inverse Analysis (Generate P/T). Unlike the burn rate reduction, the inverse analysis, generation of a pressure history, does not require a pressure-time file; thus, Option 3 is not utilized (Figure 2). Therefore, upon selecting the inverse analysis mode, the first question of the user is to provide the filename to be used for the information file as well as all the other files created during the analysis. These files and their names are shown in Table 23. Note that the files are a subset of those used in the burning rate reduction calculation (Table 19). (As before, a:test1 and a:testpgen are simply example file names.)

Table 23. Files and File Names Utilized in the Inverse Analysis

The following file names will be used:			
Master File	:	a:test1.mas	Created in Option 1
Information File	:	a:testpgen.inf	Created now in Option 4
Output File	:	a:testpgen.out	Created in Option 6
Graphics File	:	a:testpgen.dat	Created in Option 6
Pause - Please enter a blank line (to continue) or a DOS command.			

Next, the time step in milliseconds to be used in the pressure generation is requested. As in the burn rate reduction, the user is then prompted for specific hardware and charge information. This information is identical to the burn rate reduction, see Table 21. However, unlike the burn rate reduction calculation, to generate a pressure history the propellant linear burning rate must be known. BRLCB allows the burning rate to be entered in one of two ways, as indicated in Table 24.

Table 24. Methods for Entering Propellant Burning Rate Information

Enter the method by which the burn rate information will be entered.
1. bP^n burn rate law one law for each layer 2. Table of pressure vs. rate
Enter your choice by number (1–2).

In Option 1 (bP^n burn rate law), the program can only accommodate one law per grain layer. Under the second option, tabular pressure vs. rate, no such restriction is imposed. Burn rates at intermediate pressures are obtained through linear interpolation of the table of log (pressure) and log (rate). The information file is then written and the program returns to the main BRLCB menu.

2.5.3 Surface Area Analysis. Required input for the surface area analysis is identical to the burn rate reduction analysis, except that information concerning the propellant burning rate is required. This information is obtained as in the inverse analysis (Table 24).

2.5.4 Interrupted Burner. Required input for the interrupted burner analysis is identical to the burn rate reduction analysis.

2.5.5 ETC Reduction. The ETC reduction is essentially a burn rate reduction for pressure-time data obtained in an experimental firing in which an electrically generated plasma has been injected into the closed chamber during the propellant combustion. Thus, in addition to the information required for the burn rate reduction analysis, information concerning the electrical energy injected into the closed chamber is required. BRLCB expects the electrical energy information to be contained in a separate file. The prompt for this file name (Table 25) follows after the pressure-time data file is examined and the time step verified.

Table 25. Prompt for Electrical Energy File

For the ETC reduction, a file of cumulative electrical energy vs. time is required. The time must match the time in the pressure-time file, the units are seconds. The electrical energy is in units of megajoules (MJ). Enter the file name.

For this option to function properly, the time step in the electrical energy file must be the same as the time step of the pressure-time file and must be aligned in time with the pressure-time data. Note that the file is to contain the cumulative electrical energy in megajoules. In addition to the electrical energy file name, the user will also be asked for the total electrical energy in megajoules (MJ).

2.6 <u>Option 5, Smooth Pressure-Time Data (Program MKSMOOTH.EXE)</u>. In Option 3 (Prepare Pressure-Time Data), pressure-time data are imported into the BRLCB program; however, no attempt is made in that option to "massage" or prepare the data for the desired BRLCB calculation. Even if no modifications to the pressure-time data imported in Option 3 is desired by the user, Option 5 must still be executed in order to prepare the data in a format expected by the data analysis program (Option 6). Table 26 summarizes the data massaging available and indicates whether the manipulation will automatically be performed or is optional.

Table 26. Data Preparation Options Available in BRLCB

Wildpoint removal	Optional
Reduce number of data points	Automatic
Smoothing data	Optional
Calculation of dP/dt	Automatic
Make data monotonic increasing	Optional

The option begins by requesting a file name. As discussed in Options 3 and 4, this file is the file name entered in Option 3 without extension. The program will automatically append the correct extensions (.PVT for the pressure-time data and .INF for the information file). As indicated in the previous section, this option will create a file with the same file name but with an extension of .PDT. Once the file name is obtained, the program will display the smoothing and differentiation options, as shown in Table 27.

Table 27. BRLCB Smoothing and Differentiation Options

Smoothing and Differentiation Options	
1.	Use a fixed bridge length (slivering not considered).
2.	Use a "floating" bridge length (slivering not considered).
3.	Use a fixed bridge length (slivering considered).
4.	Use a floating bridge length (slivering considered).
5.	Exit
Please enter your choice.	

Essentially, smoothing and differentiating is performed using a weighted average about each point. For smoothing, only the pressure data are utilized; for differentiation, both the pressure data and time step are used. The number of points used in the averaging is called the "bridge length." In BRLCB, the bridge length can vary from 5 to 35 points, but must be an odd number. Coefficients for both the smoothing and differentiation are listed in Appendix M, contained in volume 2 of this report. To illustrate, consider using a 5-point bridge length for smoothing the 50th pressure data value, P50. Let s1–s5 be the smoothing coefficients. Then, the smoothed pressure value which will replace the 50th pressure point is

$$s1(P48) + s2(P49) + s3(P50) + s4(P51) + s5(P52) \quad . \tag{6}$$

If a fixed bridge length option is selected (Options 1 and 3), then that bridge length will be used for all the data except for data points at the beginning and end of the data record where the bridge length is adjusted so that indices for the data outside the data bounds are not requested. For example, the first two and last two data points are never smoothed; data point 3 is smoothed with a bridge length of 5; data point 4 with a bridge length of 7; etc. Using the floating bridge length options (Options 2 and 4), results in the program automatically computing the bridge length to use with each point. This bridge length will vary with each point and is selected so that the difference between the highest and lowest pressure in the smoothing is less than 10% of the maximum observed pressure for the firing. The same bridge length computed for the smoothing is utilized in the differentiation. Additional details on the smoothing and differentiation methods can be found in a report by Doman (1988).

Slivering refers to the point when the smallest propellant web has burned through and is often accompanied by a distinct change in the slope of the pressure-time curve. Smoothing, using data points on both sides of this point in the pressure-time curve, can distort the data which will be reflected in the computed burning rates. If the user selects either Option 3 or 4, smoothing and differentiation up to and after the slivering pressure are performed independently. However, BRLCB does not compute the pressure associated with the slivering event. This must be supplied by the user.

(Note: The derivative of the pressure, dP/dt, is not utilized in any of the calculational modes of BRLCB. However, it is computed since this information is utilized by some researchers and propellant formulators to determine certain propellant characteristics, namely, "relative quickness.")

As indicated in Table 26, some of the data preparation options are automatic while others are optional. To not perform either the wildpoint removal or smoothing, enter a zero when the program requests the number of wildpoint or smoothing passes to perform. (Note: Multiple wildpoint removal and smoothing passes are permitted in BRLCB.) As for making the pressure data monotonic, which will improve run time, make the desired choice when prompted. One addition option is available for the wildpoint removal. If wildpoint removal is selected, the user is able to indicate a tolerance for keeping or rejecting a point. The prompt for this option is shown in Table 28.

Table 28. Prompt for Tolerance on Wildpoint Removal

This program allows the user to enter a value to determine what the cutoff will be for discarding or keeping wildpoints or outliers. The value entered can be any number greater than zero. The closer to zero, the tighter the tolerance on the wildpoints.
Enter the value for the tolerance on the wildpoints. A value of 5 is generally used.

Essentially, the value entered can be thought of as the number of standard deviations required for a point to be considered an outlier or wildpoint. Additional details can be found in Doman's report (1988).

The actual flow of the data preparation in this option is:

1. Wildpoints are removed from the entire data set if the option is selected. The number of wildpoint passes selected by the user are performed consecutively at this point.

2. The number of data points are reduced. Points are deleted from the beginning of the file so that no point with a pressure below 80% of the theoretical igniter pressure is retained. All points after the maximum observed pressure are also deleted. A summary of the deleted points is provided to the user, see Table 29.

Table 29. Summary of Deleted Data Points

The pressure due to the igniter is:	MPa
The starting pressure value is:	MPa
N points have been deleted.	
This corresponds to a time delay of:	ms
The indices are:	
Pause - Please enter a blank line (to continue) or a DOS command	

Note: If the ETC burn rate computation has been selected, data points in the electrical energy file will be eliminated in an identical manner to maintain the time alignment between the two files.

3. The reduced data file is smooth with the number of passes selected by the user according to the selected smoothing option.

4. The pressure derivative is computed on the smoothed data.

5. The data file is further reduced in size so that no data point after the data point when the theoretical igniter pressure (with heat loss considered) is first obtained has a pressure below the igniter pressure. (Note: In the analysis, the igniter is considered to be all burnt so the deleted data points would not be utilized in the computation.)

6. The pressure data are made monotonically increasing if that option is selected.

7. The .PDT created by this option is written with the format given in Table 30. However, a maximum of 999 points will be saved in this file. If points are deleted, the deletion will start from the beginning of the data. The reduction in points is by truncation, not decimation. (Column 4 is included for the ETC reduction only.)

Table 30. Format of .PDT File

Column 1 Time (s)	Column 2 Pressure (MPa)	Column 3 dP/dt (Million MPa/s)	Column 4 Electrical Energy (MJ)

Note: When data points are deleted, the time is adjusted so that the first data point has time 0.0 s.

2.7 Option 6, Perform Data Analysis (Program MKCAL.EXE). As the name indicates, this option performs the actual data analysis indicated in Option 4, Prepare Firing Information File, by the user. The user is first prompted to enter the file name (the common .INF, .PVT, and .PDT file name) associated with the analysis. As discussed in previous sections, the file extension is not included. (Note: Entering a 10 at the file name prompt will allow the user to change the default convergence criteria utilized in the program for computing mass burned. The current default is 1E-5.) After the file name is entered, the program will access all necessary files and begin the analysis. First, the program will determine the mass of air in the closed chamber based upon the data contained in the .INF file. The user may elected to ignore the air mass in the bomb (e.g., the closed chamber was evacuated before the firing) and is provided this option, as shown in Table 31.

Table 31. Prompt for Air Mass Option

The computed mass of air in the bomb is: _________ g. Do you wish to change this value to 0.0 g? (yes = 1, no = 2)
Enter your choice.

Next, information concerning the heat loss is presented. BRLCB uses the term heat loss fraction which is computed as

$$\text{Heat Loss Fraction} = 1 - \frac{\text{Observed Maximum Pressure}}{\text{Theoretical Maximum Pressure}} \quad . \qquad (7)$$

If the analysis mode is 1 (Burn Rate Reduction), 3 (Surface Area Analysis), or 5 (ETC Reduction), the heat loss information will be presented as shown in Table 32. In general, a different value for the heat loss fraction should not be entered. The information is provide mostly as a "sanity" check. Observed maximum pressure should never exceed the theoretical maximum pressure. If it does, the input values to the program should be carefully examined. On average, the heat loss should be in the 5%–10% range (LOVA propellants up to 20%), heat loss fraction of .05–.1. When heat losses greatly exceed these values, the input data to the program, data recording, and/or experimental procedures should be examined.

Table 32. Presentation of Heat Loss Information

**Based on the following pressure information: Observed maximum pressure (MPa) value of = _______ Maximum theoretical pressure (MPa) value of = _______ The current heat loss fraction is: _______
Enter a different value? (yes = 1, no = 2)

However, if analysis mode 2 (Pressure Generation) or 4 (Interrupted Burner) is selected, a value for the heat loss fraction must be entered. The prompt to enter the heat loss fraction is given in Table 33.

Table 33. Prompt for Heat Loss Fraction, Analysis Modes 2 and 4

For the pressure generation option (Option 2) or the interrupted burner option (Option 4), a heat loss fraction must be entered. The heat loss fraction is in the range of 0.0–1.0. For example, a value of 0.1 means 10% of the total energy will be considered lost as heat to the chamber wall during the calculation.
Enter the value for the heat loss factor. A decimal between 0.0 and 1.0.

After air mass and heat loss are handled, the analysis is started. As mentioned earlier, the model assumes that the igniter is all burnt at the start of the analysis. Thus, points at the beginning of the data file may be ignored. Information concerning the ignored data points is provided to the user, as shown in Table 34.

Table 34. Information Concerning Data Points Ignored in the Calculation

For the calculation to be performed correctly, all pressures must be above the igniter pressure. For the current data set points had to be deleted to obtain all pressures above the igniter pressure. Information relative to the deleted data points is:
Number of points deleted: Time interval of deleted points (ms): Igniter pressure (MPa):

2.8 Option 7, Prepare Output (Program MKOUT.EXE). This option, as the name indicates, is used to prepare both hard copy and/or magnetic output for the analysis. The option provides for computation of burn rate laws and graphical output as well as a one page summary sheet for burn rate reductions (analysis modes 1, 4, and 5).

Appendix C contains a sample output from BRLCB. First, the input information provided by the user is echoed. Next is a complete listing of all data used in the computation and information concerning maximum chamber properties, together with heat loss information. Tabular data from the computation follow. Table 35 summarizes the information for the nine columns of the tabular data.

Table 35. Structure of Tabular Data Output for BRLCB

Column	Information	Units
1	Computational step	–
2	Propellant layer	--
3	Time	ms
4	Chamber pressure	MPa
5	Unburned propellant mass	g
6	Burn rate	cm/s
7	Propellant surface area	cm^2
8	Average chamber temperature	K
9	Depth burned	cm

This option also allows the user to perform a Fast Fourier Transform (FFT) analysis of computed burning rates if the rates display a large amount of oscillations. Trial and error will be required to determine the best cut-off value for the FFT frequency. Generally, selecting a low frequency will provide the best results. Figure 19 shows burning rates computed for an M5 propellant. As can been seen in the figure, some oscillation of the burning rate is present. After performing a low pass filter on the data, the burning rate shown in Figure 20 is obtained which displays much less oscillation. A comparison of the two burning rates is provided in Figure 21. In the program, the user is able to determine the effect of the FFT and decide whether to use the original or filter burning rate data.

2.9 Sample Problem. On the diskette containing the source files for BRLCB is a subdirectory labeled SAMPLE. This directory contains all the files from a sample BRLCB burning rate reduction (see Table 36). The information can be used either to verify the computational portion of the BRLCB program or provide the user with a "practice" set of data to utilize in learning how to run the entire BRLCB program for burning rate reduction.

Table 36. Files in Subdirectory SAMPLE

TEST1.PT
TEST1.MAS
TEST1.PVT
TEST1.INF
TEST1.BR
TEST1.PDT
TEST1.OUT
TEST1.DAT
TEST1.PRT

To verify the computational portion of the program, follow the following procedure.

1. Copy the files TEST1.INF, TEST1.PDT, and TEST1.BR to a disk in drive A (these files must be on drive A).

2. Change directory to the directory containing the BRLCB program.

3. Start the program by typing BRL and select Option 6.

4. At the file name prompt, enter A:TEST1, accept the air mass as computed, and set the heat loss to 0.0.

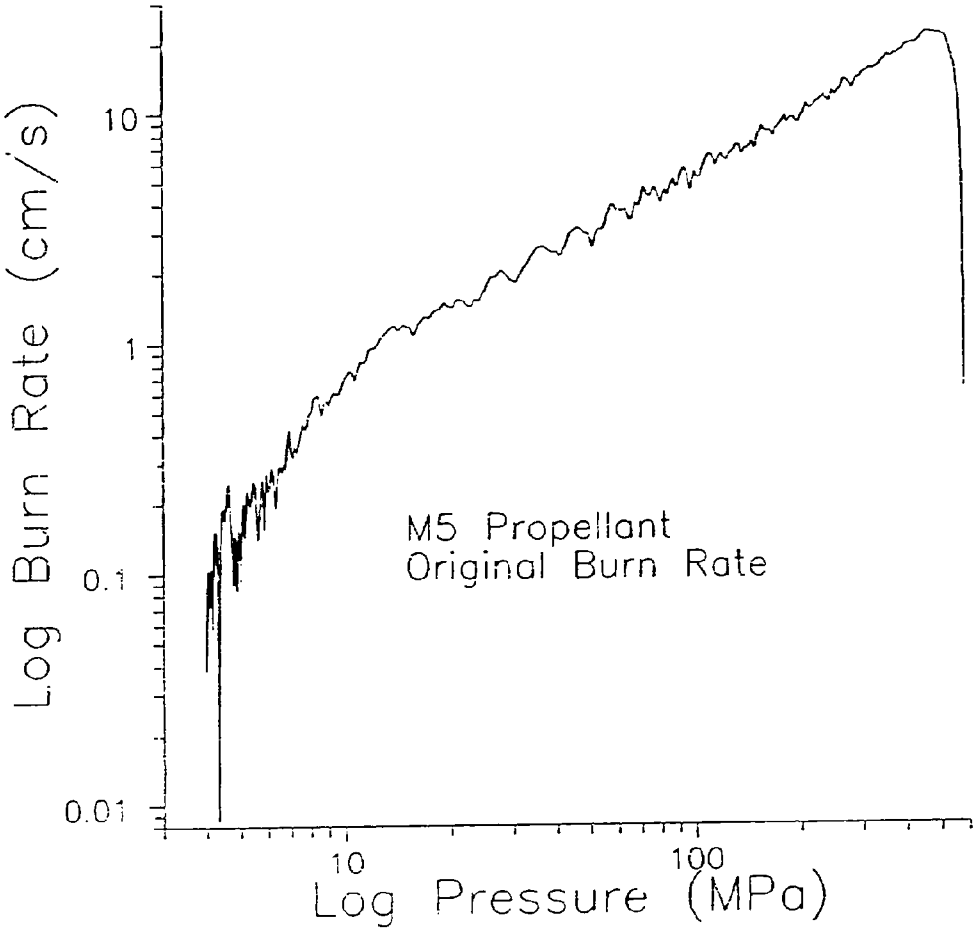

Figure 19. Original unfiltered M5 burning rate data.

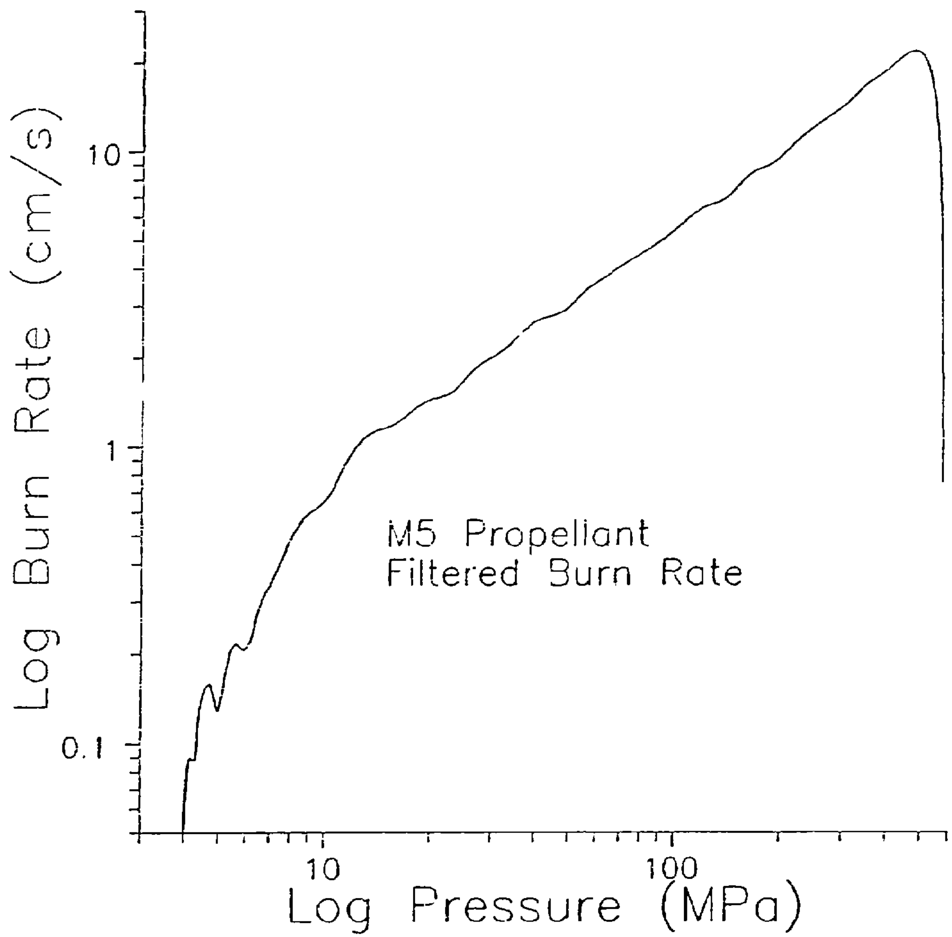

Figure 20. Filter (low pass) M5 burning rate data.

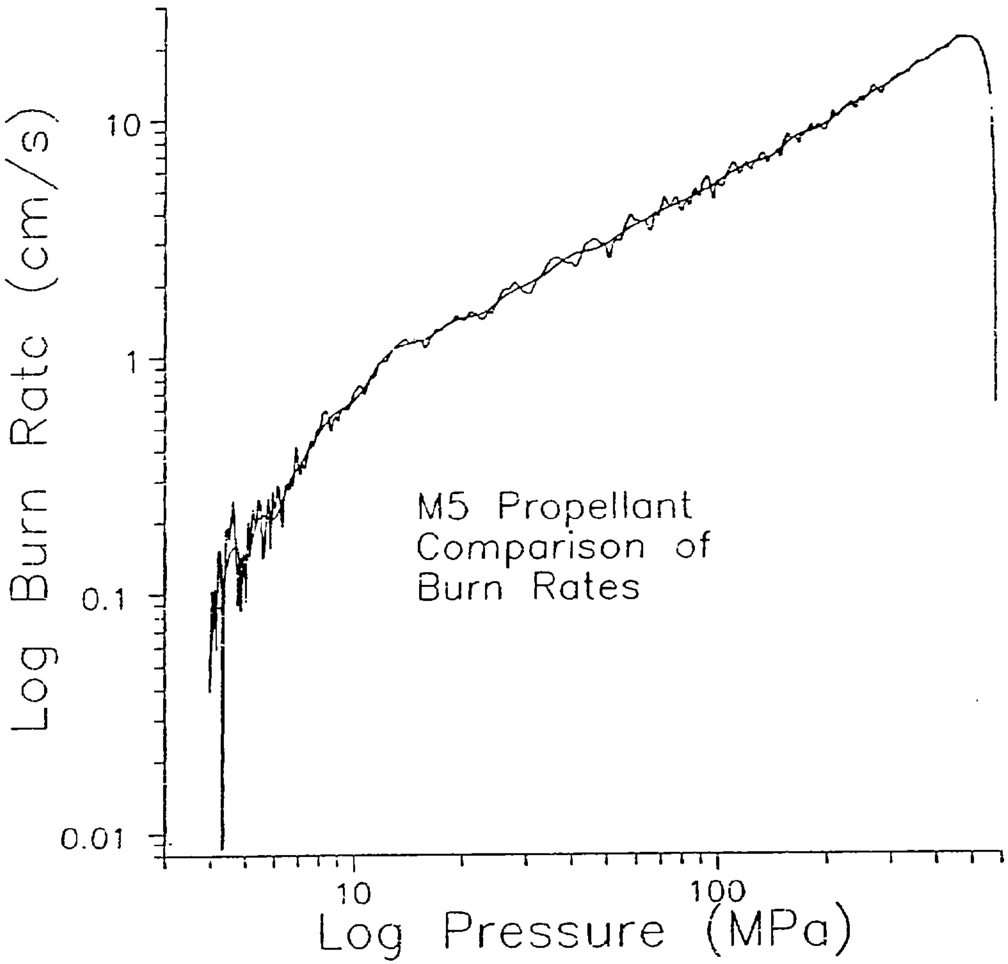

Figure 21. Comparison of filtered and unfiltered M5 burning rate data.

5. When the program returns to the main menu, select Option 7. Respond to the file name prompt again with A:TEST1 and do not perform any filtering on the burn rate data.

The printed output can be compared with the information in the file TEST1.PRT. If these files are not identical, repeat the process.

Instead of simply verifying the computational portion of the program, it is recommended that the user exercise all the options of the program by using the sample data to perform the burning rate reduction from the beginning. In this case, only one file (TEST1.PT) needs to be copied to drive A (or to the directory where the BRLCB executable programs are located). Then, the user should run all options (1–7) except Option 2, in order. Necessary information for the reduction is listed in Table 37. Results can be compared with the file TEST1.PRT.

Table 37. Information Required for Sample Burning Rate Reduction

Propellant:	
Grain geometry	Sphere
Diameter	0.072 cm
Impetus	1,165.4 J/g
Flame temperature	3,680 K
Molecular weight	26.25323
Gamma	1.2155
Covolume	0.966 $cm^3/9$
Density	1.6 g/cm^3
Mass	13.1 g
Initial temperature	294 K
Igniter:	
Same thermochemistry as propellant	
Mass	0.5 g
Initial temperature	294 K
Hardware:	
Bomb volume:	65.5 cm^3
Time Step:	
	0.025 ms

3. THEORETICAL ANALYSIS OF CLOSED-CHAMBER COMBUSTION

A closed chamber is a rather simple device which monitors transient combustion with a single diagnostic—a wall-mounted pressure transducer. Except for the initial conditions, the pressure-time record is the only information available to deduce an effective linear regression rate of the material confined in the chamber. Of course, predicting this regression (or burning) rate is not a new problem. A number of methods of varying levels of sophistication have been advanced over the years, as illustrated in Robbins and Horst (1976); Price and Juhasz (1977); Oberle, Juhasz, and Griffie (1987); Robbins and Lynn (1988); and references therein. Although a comprenehsive review is beyond the scope of the present report, it appears that two basic approaches have been employed. The first method derives a closed-form solution for mass remaining (or consumed) in the chamber as a function of the experimental value of pressure. The second method derives a differential equation for the rate of change of propellant mass which must be numerically integrated in time. This differential equation, of course, must be accompanied by some estimate of the time derivative of chamber pressure from the experimental data.

In the authors' opinion, the first method (closed-form solution) is superior. The second method can be encumbered by stability and accuracy problems associated with forward time integration and also requires that the experimental pressure-time data be differentiated. With an objective to eliminate as many sources of error as possible, the present analysis will be based on a closed-form solution (first method). Although derived independently, the analysis shares the general approach first outlined by Robbins and Horst (1976).

The closed chamber analysis developed here invokes several assumptions common to a "well-stirred reactor." Velocities within the chamber are assumed vanishingly small, and, hence, balance of momentum implies spatially uniform pressure. For consistency, kinetic energy is assumed negligible compared to stored thermal and chemical energy. All other properties of the gas phase within the chamber are spatially invariant as the result of the "well-mixed" assumption. However, solid-phase properties, as discussed below, can vary as a function of 1) the particular segment of propellant which is burning and 2) how much mass of that segment has been consumed. Thus, properties of the combustion gases entering the chamber at any given time will depend upon the amount of solid material which has been consumed by the combustion process. The chamber initial condition assumes that the igniter material has been consumed, although a description of igniter combustion could easily be added in the future.

3.1 Variable Property Description. The present closed-chamber combustion analysis is not restricted to homogeneous solid propellant material with spatially uniform properties. Provisions are made for propellant properties such as density, stored thermal energy, etc. to have a specified variation as a function of the depth beneath the initial surface, which is related to the amount of material which has burned away. Although the propellant properties must be time invariant, the description of spatial variability has substantial flexibility while at the same time incorporating the previous description of layered propellant (Oberle and Kooker 1989). Consider the schematics shown in Figures 22–24, where ψ represents any propellant property and x represents a coordinate which is zero at the initial surface and taken as positive in the direction of the interior of the propellant grain. The propellant material is then subdivided into N layers or segments in the x coordinate, where the segments do not have to have equal thickness. Let a subscript 1 denote the value associated with the beginning of the segment and a subscript 2 denote the value at the end of the segment. A basic assumption of the analysis is that property variations within a given segment are linear in the x coordinate. Between segments, however, no continuity is assumed or required; both the function and its spatial derivatives may be discontinuous. The flexibility provided by this description is illustrated in Figures 22–24. The continuous property variation shown in Figure 22 is enforced by setting

$$\psi_{2_i} = \psi_{1_{i+1}} \quad for \ 1 \le i \le N - 1 \quad , \tag{8}$$

where the accuracy of the representation by linear segments will be governed by the chosen thickness of the segments. A material with distinct layers (see Figure 23), each of which has uniform properties, is described with

$$\psi_{1_i} = \psi_{2_i} \quad for \ 1 \le i \le N \quad . \tag{9}$$

And, as sketched in Figure 24, the analysis will also describe a material composed of a combination of distinct layers, each of which has variable properties.

An analysis of closed-chamber combustion must relate chamber pressure, at any instant of time, to the amount of material consumed by the combustion process. This requires some type of "progress variable" to monitor the extent of completion of the combustion process. An additional role for this variable is to link the instantaneous value of burning surface area to the amount of solid propellant

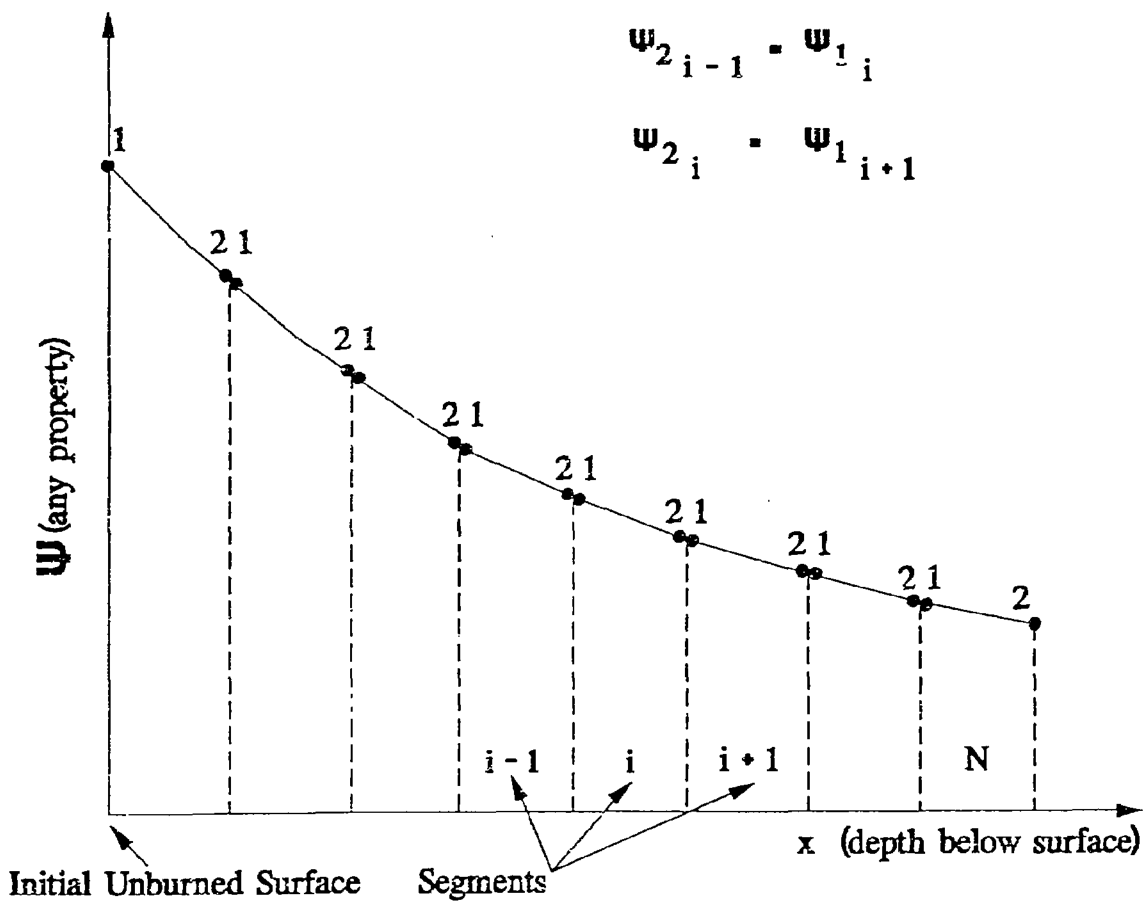

Figure 22. Continuous property variation.

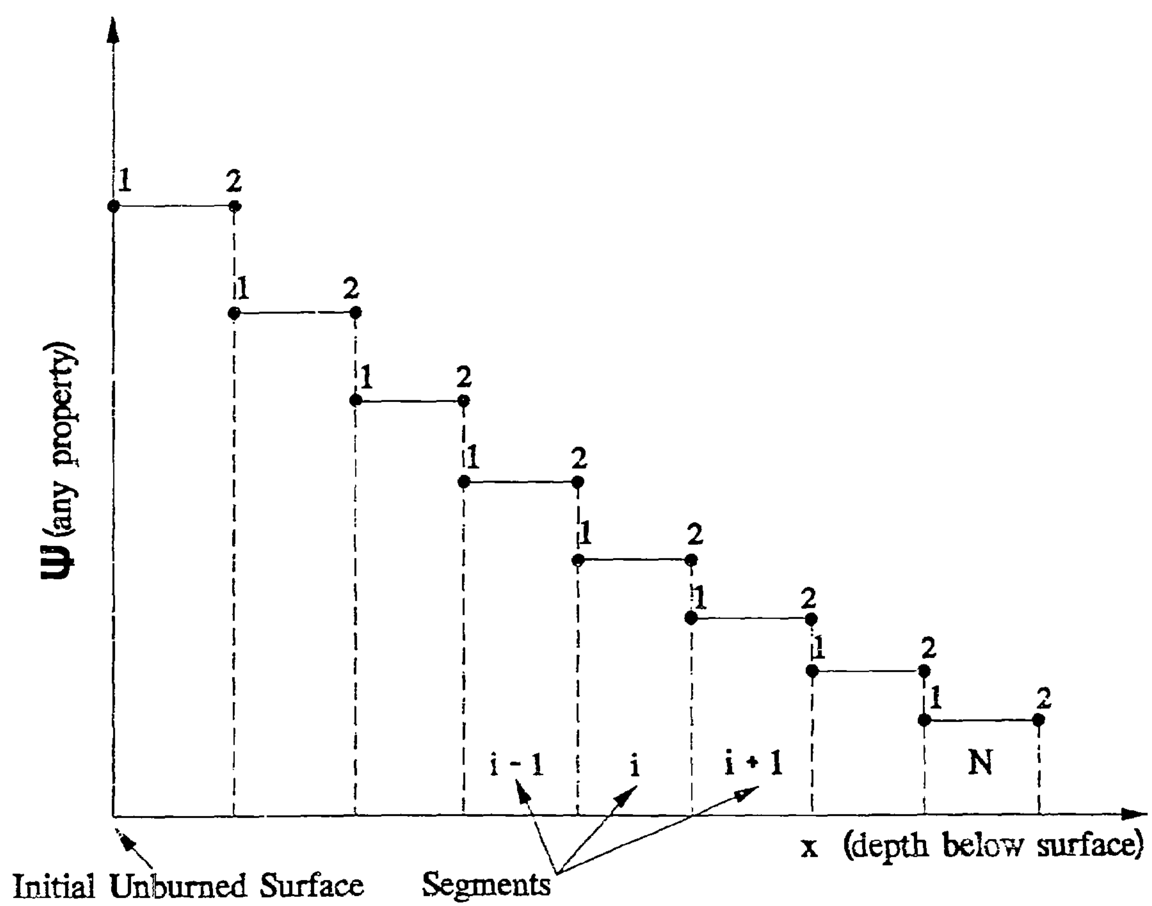

Figure 23. Distinct layers.

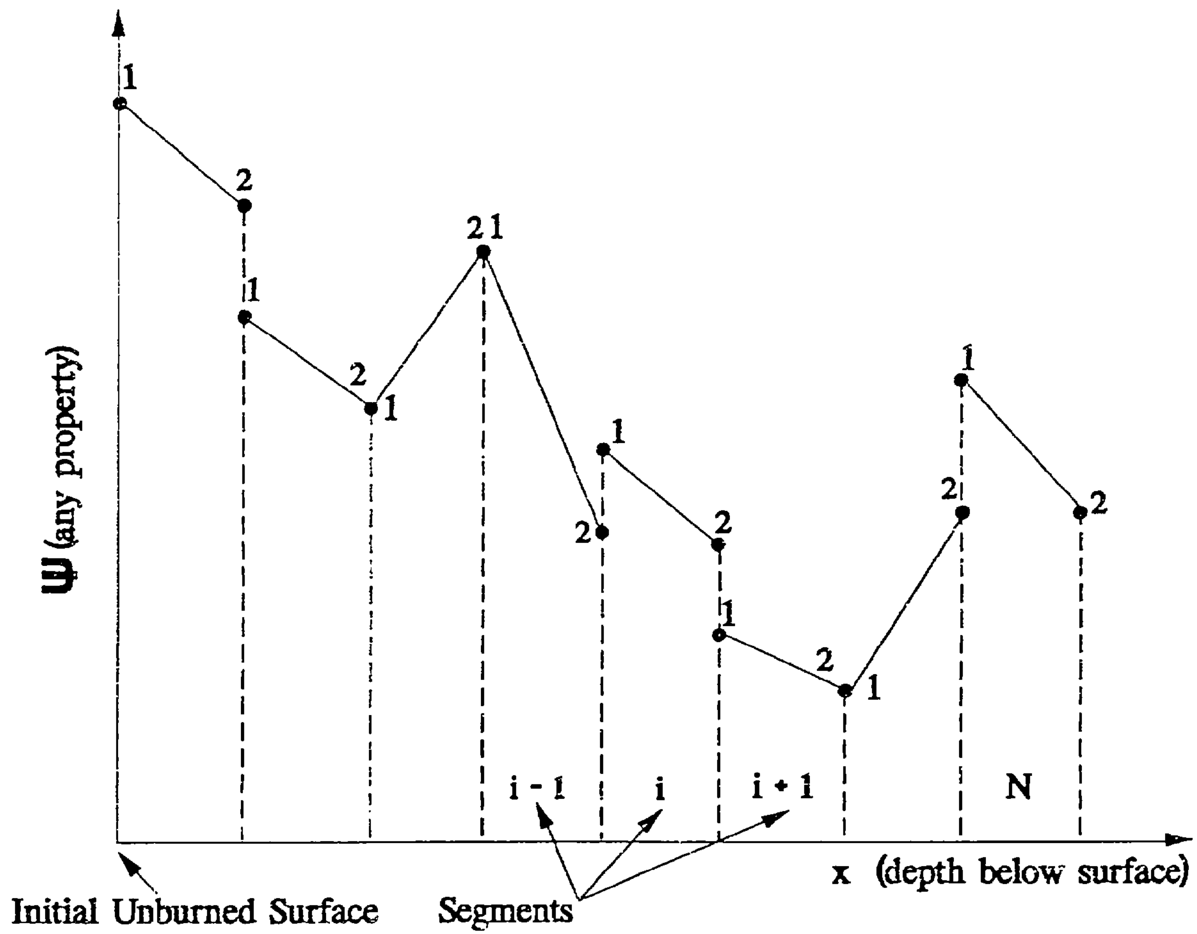

Figure 24. Hypothetical combination: Distinct layers with variable properties.

mass which has been consumed. The present analysis will choose the progress variable to be the fraction of propellant mass in segment "i" remaining in the chamber, denoted as ξ_i and defined

$$\xi_i \equiv \frac{m_{s_i}}{m_{s_i}^o} \tag{10}$$

where

$m_{s_i}^o$ = solid propellant mass *initially* contained in segment "i"

m_{s_i} = solid propellant mass of segment "i" remaining in chamber.

Note that when

the segment is unburned ==> $\xi_i = 1$

the segment is consumed ==> $\xi_i = 0$.

Clearly then, the fraction of propellant mass of segment "i" which has been consumed is

$$1 - \xi_i .$$

This quantity is directly related to the depth of material which has been consumed by the combustion process; the relationship is given by an integral. Assume that a differential volume element can be represented as

$$dV = A(x)\, dx$$

where "x" is the depth coordinate discussed above and $A(x)$ is the grain surface area at depth "x". Note that the direction of coordinate x is always normal to the surface $A(x)$. Now let x_{1_i} denote the depth at which segment "i" begins, and x_{2_i} denote the depth at which it ends. When combustion of segment "i" is underway (i.e., $x_{1_i} < x < x_{2_i}$), then the mass of segment "i" which has been consumed is simply

$$\int_{x_{1_i}}^{x} \rho_s(z) A(z)\, dz \ .$$

Then the relationship between $1 - \xi_i$ (the fraction of propellant mass in segment "i" which has been consumed) and $x - x_{1_i}$ (the depth burned of segment "i") is defined by the mass balance,

$$(1 - \xi_i)\, m_{s_i}^{o} = \int_{x_{1_i}}^{x} \rho_s(z)\, A(z)\, dz \ . \tag{11}$$

This represents the crucial link between grain geometry (depth burned and surface area), variable propellant density, and mass consumed by the combustion process. In practice, given a value of ξ_i, an iteration procedure is used to determine the corresponding value of "x" which balances Equation (11) to within some tolerance. Also note the obvious equality when $x = x_{2_i}$, i.e.,

$$m_{s_i}^{o} = \int_{x_{1_i}}^{x_{2_i}} \rho_s(z)\, A(z)\, dz \ . \tag{12}$$

Now the assumed linear dependence of any property Ψ can be expressed as

$$\Psi_i(x) = \Psi_{1_i} + (\Psi_{2_i} - \Psi_{1_i}) \frac{(x - x_{1_i})}{(x_{2_i} - x_{1_i})} \ . \tag{13}$$

Because the present analysis must allow for solid propellant with variable properties, the balance equations for combustion will be a function of certain average values which account for the "history" of the property variation to that time. The average value of a quantity (in the i^{th} segment) which has been consumed is simply

$$\bar{\Psi}_i(x) = \frac{\int_{x_{1_i}}^{x} \Psi_i(z)\, A(z)\, dz}{\int_{x_{1_i}}^{x} A(z)\, dz} \ . \tag{14}$$

The average value of a quantity (in the i^{th} segment) remaining in the chamber (not yet consumed) is then

$$\bar{\Psi}_i(x) = \frac{\int_x^{x_{2_i}} \Psi_i(z)A(z)\,dz}{\int_x^{x_{2_i}} A(z)\,dz} . \tag{15}$$

Note that if the quantity $\Psi(x)$ is uniform (constant value, e.g., Ψ_i) in the "ith" segment, as shown in Figure 23, then Equations (14) and (15) reduce to

$$\bar{\Psi}_i(x) = \Psi_i . \tag{16}$$

Thus, in the special case of constant property layers, Equation (16) defines both the average value of the quantity which has been consumed and the average value of the quantity remaining in the chamber.

3.2 Governing Equations. The equations governing combustion of solid propellant in a closed chamber are straightforward. Since no mass enters or leaves the chamber, conservation requires that any solid mass consumed in the combustion process must reappear in the gas phase. Since the velocities of both phases are assumed negligible, a momentum balance in the chamber reduces to a statement of spatially uniform pressure. The balance of energy monitors the transfer of stored chemical energy in the solid to the gas during combustion, and accounts for any heat loss through the chamber walls. Finally, a gas-phase equation of state must relate pressure, temperature, and gas volume.

Some notation is required to express these balance laws. For a chamber of fixed volume, let

P_{ch} ≡ chamber pressure,
T_{ch} ≡ chamber temperature,
V_{ch} ≡ closed chamber volume
V_{free} ≡ chamber volume not occupied by solid material.

Then define

b ≡ covolume,

C_v ≡ specific heat at constant volume, [here, $\Re / (\gamma - 1)$]

e ≡ specific internal energy,

m ≡ solid propellant mass remaining in chamber,

M ≡ molecular weight,

Q_w ≡ cumulative heat loss to chamber walls

$\Re$ ≡ universal gas constant/molecular weight = R_o / M,

γ ≡ C_p / C_v

ρ ≡ density.

Define the subscripts

$(\ )_s$ => pertains to solid phase (solid propellant),

$(\ )_g$ => pertains to gas phase (combustion products),

$(\ )_{ig}$=> pertains to gas-phase igniter products,

$(\ )_a$ => pertains to air initially in chamber,

$(\ )_{ch}$ => pertains to chamber conditions,

$(\ )_1$ => evaluated at the beginning of the segment,

$(\ )_2$ => evaluated at the end of the segment,

$(\ )_i$ => pertains to the ith segment or layer of the solid propellant.

A superscript "o" means

$(\ )^o$ => pertains to the initial condition (at time zero).

For each segment i, the initial conditions provide $m_{s_i}^o$, the initial mass of propellant in segment i. At any other time, m_{s_i} is the mass of propellant in segment i remaining in the chamber as solid. The ratio of these two quantities is chosen as the progress variable ξ_i. Thus by definition,

$$m_{s_i}(t) = m_{s_i}^o \cdot \xi_i(t) \quad , \tag{17}$$

and mass conservation for each propellant segment requires that

$$m_{g_i}(t) = m_{s_i}^o - m_{s_i}(t) = m_s^o \left[1 - \xi_i(t)\right] \quad . \tag{18}$$

Subscript i denotes properties associated with one of the N segments of the solid propellant material. It is assumed that the segments are numbered sequentially, with the segment labelled $i = 1$ at the outer surface of the unburned grain. Note that at any time before segment i begins to burn, ξ_i is unity; at any time after segment i has been consumed, ξ_i is zero.

Expressions for the gas-phase equation of state and the energy balance for the chamber will depend upon certain time-varying average quantities; i.e., thermochemical and physical properties of the propellant. These average values at time t are functions of the solution at time t. Clearly, the desired solution will require an iteration procedure. Define the following average quantities which are functions of the final solution at time t:

$$\bar{\rho}_{s_i} \equiv m_{s_i}^o \text{ / (Average density of material not yet consumed.)} \quad , \tag{19}$$

$$\bar{e}_{s_i}^o \equiv m_{s_i}^o * \text{(Average specific internal energy of material not yet consumed)} \quad , \tag{20}$$

which employ Equation (15), and

$$\bar{b}_{g_i} \equiv m_{s_i}^o * \text{(Average covolume of material consumed.)} \quad , \tag{21}$$

$$\bar{C}_{v_{g_i}} \equiv m_{s_i}^o * \text{(Average specific heat at constant volume of material consumed.)} \quad , \tag{22}$$

$$\bar{\Re}_{g_i} \equiv m_{s_i}^o * \begin{bmatrix} \text{(Average value of universal gas constant/molecular} \\ \text{weight of material consumed.)} \end{bmatrix} \quad . \tag{23}$$

which employ Equation (14). It is important to note that Equations (19) and (20) define the average of a quantity not yet consumed, whereas Equations (21)–(23) define the average of a quantity which has been consumed. The reader should note that, as defined above, the "over bar" quantities are all functions of $m_{s_i}^o$.

A covolume equation of state for the gas mixture can be written,

$$P_{ch}\left\{V_{free} - \text{volume occupied by gas molecules}\right\} = R_o\, T_{ch} \sum_{i=1}^{N} \{\text{no. moles of gas}\} \quad . \tag{21}$$

The volume of the chamber not occupied by the solid propellant (V_{free}) is simply

$$V_{free} = V_{ch} - \sum_{i=1}^{N} \bar{\rho}_{s_i} \cdot \xi_i \quad . \tag{22}$$

Then the equation of state [Equation (21)] becomes

$$P_{ch}\left\{V_{ch} - \sum_{i=1}^{n} \bar{\rho}_{s_i}\, \xi_i - b_{ig}\, m_{ig} - b_a\, m_a - \sum_{i=1}^{N} \bar{b}_{g_i}\, (1 - \xi_i)\right\}$$
$$= T_{ch}\left\{\Re_{ig}\, m_{ig} + \Re_a\, m_a + \sum_{i=1}^{N} \bar{\Re}_{g_i}\, (1 - \xi_i)\right\} \quad . \tag{23}$$

For convenience, define the terms

$$K_1 \equiv V_{ch} - b_{ig}\, m_{ig} - b_a\, m_a - \sum_{i=1}^{N} \bar{b}_{g_i} \quad ,$$

$$K_2 \equiv \Re_{ig}\, m_{ig}\, m_{ig} + \Re_a m_a + \sum_{i=1}^{N} \bar{\Re}_{g_i}$$

neither of which are constant; both must be updated in the iteration procedure. Equation (26) can then be written,

$$P_{ch}\left\{K_1 - \sum_{i=1}^{N}\left(\bar{\rho}_{s_i} - \bar{b}_{g_i}\right)\xi_i\right\} = T_{ch}\left\{K_2 - \sum_{i=1}^{N}\bar{\Re}_{g_i}\,\xi_i\right\} . \tag{27}$$

To write the energy balance in the chamber, let E represent the total energy contained in V_{ch}. Then the first law of thermodynamics states that

$$E^{o} = E(t) + Q_w(t) \tag{28}$$

where $Q_w(t)$ is the cumulative heat loss from the chamber. For the ETC reduction, $Q_w(t)$ = cumulative heat low-cumulative electrical energy input. The initial energy E^o is simply,

$$E^{o} = m_{ig}\,e_{ig}^{0} + \sum_{i=1}^{N}\bar{e}_{s_i}^{o} \tag{29}$$

which neglects stored thermal energy in the solid material at the initial temperature compared to stored chemical energy. For any time greater than zero, the igniter material has been converted to gaseous products, and the total energy can be represented as

$$E(t) = \sum_{i=1}^{N}\bar{e}_{s_i}^{o}\,\xi_i + T_{ch}\left\{m_{ig}\,C_{v_{ig}} + m_a\,C_{v_a} + \sum_{i=1}^{N}\bar{C}_{v_{g_i}}\,(1-\xi_i)\right\} . \tag{30}$$

Hence, the first law in Equation (28) becomes

$$E^{o} - Q_w(t) = \sum_{i=1}^{N}\bar{e}_{s_i}^{o}\,\xi_i + T_{ch}\left\{m_{ig}\,C_{v_{ig}} + m_a\,C_{v_a} + \sum_{i=1}^{N}\bar{C}_{v_{gi}}\,(1-\xi_i)\right\} . \tag{31}$$

Again for convenience, define the term

$$K_3 \equiv m_{ig}\,C_{v_{ig}} + m_a\,C_{v_a} + \sum_{i=1}^{N}\bar{C}_{v_{g_i}}$$

which also must be updated in the iteration procedure. Solving Equation (31) for T_{ch},

$$T_{ch} = \frac{E^o - Q_w(t) - \sum_{i=1}^{N} \bar{e}^o_{s_i} \xi_i}{K_3 - \sum_{i=1}^{N} \bar{C}_{v_{g_i}} \xi_i} \quad . \tag{32}$$

The analysis which follows is based on the convention that propellant segments are labeled $i = 1,...,N$ in the order in which combustion will reach them. Thus, when segment k is burning ($1 \le k \le N$), a) segments $1,...,(k-1)$ have been consumed $[\xi' s = 0]$, and b) segments $(k+1),...,N$ are unburned $[\xi' s = 1]$. With this convention in mind, define the following terms:

$$C_1 \equiv K_1 - \sum_{\substack{i=1 \\ i \neq k}}^{N} \left(\bar{\rho}_{s_i} - \bar{b}_{g_i}\right) \xi_i \quad ,$$

$$C_2 \equiv K_2 - \sum_{\substack{i=1 \\ i \neq k}}^{N} \bar{\Re}_{g_i} \xi_i \quad ,$$

$$C_3 \equiv K_3 - \sum_{\substack{i=1 \\ i \neq k}}^{N} \bar{C}_{v_{g_i}} \xi_i \quad ,$$

$$C_4 \equiv E^o - Q_w(t) - \sum_{\substack{i=1 \\ i \neq k}}^{N} \bar{e}^o_{s_i} \xi_i \quad .$$

Note that C_1, C_2, C_3, and C_4 must also be updated in the iteration procedure. The gas mixture equation of state, Equation (27), can then be written as

$$P_{ch} \left\{C_1 - \left(\bar{\rho}_{s_k} - \bar{b}_{g_k}\right) \xi_k\right\} = T_{ch} \left\{C_2 - \bar{\Re}_{g_k} \xi_k\right\} \quad , \tag{33}$$

and the chamber energy equation, Equation (32), becomes

$$T_{ch} = \frac{C_4 - \bar{e}^o_{s_k} \xi_k}{C_3 - C_{v_{g_k}} \xi_k} \quad . \tag{34}$$

Substituting Equation (34) into Equation (33), assuming that $P_{ch}(t)$ is given by experimental data from the chamber, the result is a quadratic equation for ξ_k, the fraction of propellant mass in segment k which has yet to be consumed.

$$Q_A \xi_k^2 + Q_B \xi_k + Q_C = 0 \tag{35}$$

where

$$Q_A \equiv \bar{\Re}_{g_k} \bar{e}^o_{s_k} - P^{(t)}_{ch} \bar{C}_{v_{g_k}} \left(\bar{\rho}_{s_k} - \bar{b}_{g_k}\right)$$

$$Q_B \equiv P_{ch} \left[C_1 \bar{C}_{v_{g_k}} + C_3 \left(\bar{\rho}_{s_k} - \bar{b}_{g_k}\right)\right] - C_2 \bar{e}^o_{s_k} - C_4 \bar{\Re}_{g_k}$$

$$Q_C \equiv C_2 C_4 - P_{ch} C_1 C_3 \quad .$$

The solution of Equation (35) is simply

$$\xi_k = - \left\{ Q_B + \sqrt{Q_B^2 - 4\, Q_A Q_C} \right\} / 2\, Q_A \quad . \tag{36}$$

This value of ξ_k is used to update all the time-varying average quantities as well as the terms (e.g., K_1, K_2, K_3) which are functions of these quantities. Then a new solution for ξ_k is obtained from Equation (36), and the process is repeated until successive iterates are equal to within some tolerance. Experience with the test cases has shown convergence to be quite rapid.

Once the solution for the ξ_k has been determined, chamber temperature $T^{(t)}_{ch}$ follows directly from Equation (34). Note that the value of chamber pressure at which the k^{th} segment "burns out" is given explicitly by $Q_C = 0$ or

$$P_{ch}\big|_{burnout} = \frac{C_2 C_4}{C_1 C_3} \quad . \tag{37}$$

Once the k^{th} segment is consumed ($\xi_k = 0$ and hence $m_{sk} = 0$), the analysis automatically assumes that the $k + 1$ segment begins burning with the initial condition $m_{s_{k+1}} = m^o_{s_{k+1}}$ or $\xi_{k+1} = 1$. When the last or N^{th} segment has been consumed, the function $m_s(t)$, the total propellant mass remaining in the chamber,

$$m_s(t) = \sum_{i=1}^{N} m^o_{s_i} \xi_i(t) \quad , \tag{38}$$

has been determined. The time derivative dm_s/dt can easily be determined by finite difference with second-order accuracy. In several checkout cases, this finite difference derivative was compared to the differential of a cubic spline and found to have the same accuracy. Given the instantaneous surface area, $A(t)$, as a function of depth burned, the effective linear regression rate is simply

$$r = \frac{dm_s/dt}{\rho_s A(t)} \quad . \tag{39}$$

It is well known that the values of linear burning rate deduced from a closed chamber pressure record will be influenced by the amount of heat (or energy) lost to the chamber boundaries or walls. In the present analysis, this is represented by the term Q_w, the cumulative heat loss to the chamber walls. Possibly because the computation of Q_w is not trivial, there seems to be no general agreement on the calculation procedure. In many cases, however, the calculation depends upon Q_{max}, the amount of heat lost to the chamber walls up to the time of maximum pressure [currently in BRLCB, Q_w is computed as $(P_{ch} / P_{chmax}) * Q_{max}$]. Q_{max} is computed in the following way: Equation (26) gives a value of T_{ch} based on the *measured* value of maximum pressure; Equation (31) is then solved for the corresponding value of heat loss, Q_{max}.

4. VALIDATION

To validate the computer implementation of the mathematical model and the various grain form functions, a series of test cases were performed. The test cases can be divided into five series with the following objectives.

Series I. Validate the computer implementation of the mathematical model through comparison with analytically generated data.

Series II. Quantify the affect of reduced accuracy in the input pressure data on the accuracy of the deduced burning rate.

Series III. Validate the grain form functions.

Series IV. Validate the ETC Burning Rate Reduction option.

Series V. Validate the computer implementation for multilayered propellants with constant properties and varying properties.

4.1 Series I Test Cases. To validate the computer implementation of the mathematical model, results from BRLCB are compared to an analytic (no numerical methods utilized) solution of the closed-chamber problem (valid only for single perforated grain with a burn rate exponent of 1) using a procedure provided by Robbins and Lynn (1988). Table 38 summarizes the input parameters used to generate the analytic data as well as the inputs to the various options of BRLCB. Sufficient information is available from the analytically generated data to validate the burning rate reduction option (1) [and, hence, the interrupted burner option (4)], the pressure generation option (2), and the surface area analysis option (3). The ETC burn rate reduction is validated in test series IV.

Test Case 1. In this test case, the pressure-time data from the analytic solution of Robbins and Lynn are used to validate the burning rate reduction (and thus the interrupted burner option) option of BRLCB. Results from the BRLCB burn rate analysis are given in Figures 25 and 26. The deduced burning rate

Table 38. Input Parameters for Robbins and Lynn Analytic Solution

Closed-chamber volume:	205.002 cm^3
Grain geometry:	Single Perforation length: 2.54 cm diameter: .635 cm perf diam: .127 cm
Propellant:	
Impetus:	1,009.5959 J/g
Flame temperature:	3,400 K
Ratio of specific heats:	1.2299
Molecular weight:	28
Covolume:	.90318 cm^3/g
Density:	1.6608 g/cm^3
Total mass:	56.69905 g + .09072 g igniter
Burn rate law:	$r = .73679\ P^{1.0}$ cm/s

is shown in Figure 25 with the corresponding percent error with the assumed burning rate given in Figure 26. As can be seen from the figures, the deduced burning rate is linear (on log-log scale) with a maximum percent error of approximately 0.002%. Thus, it appears that the computer implementation is accurately predicting propellant burn rates from closed-chamber pressure-time data.

Test Case 2. Using the same inputs (Table 38) as in the Robbins and Lynn model, BRLCB was used to generate the closed-chamber pressure-time trace shown in Figure 27. A comparison with the Robbins and Lynn generated pressure history (in terms of percent error) is provided in Figure 28. Although the maximum percent error has increased by an order of magnitude (0.02% vs. 0.002%) compared to test case 1, the authors believe that this is still within the round-off/truncation error associated with the numeric methods employed in BRLCB.

Test Case 3. As in test case 1, the analytic pressure history is used as input to the BRLCB code. However, in this test case, the assumed burn rate (Table 38) is used to determine the grain surface area profile. Thus, the surface area analysis option of BRLCB is being validated. Figure 29 shows the percent error between the BRLCB computed surface area and the Robbins and Lynn surface area. The maximum percent error is approximately 0.002%.

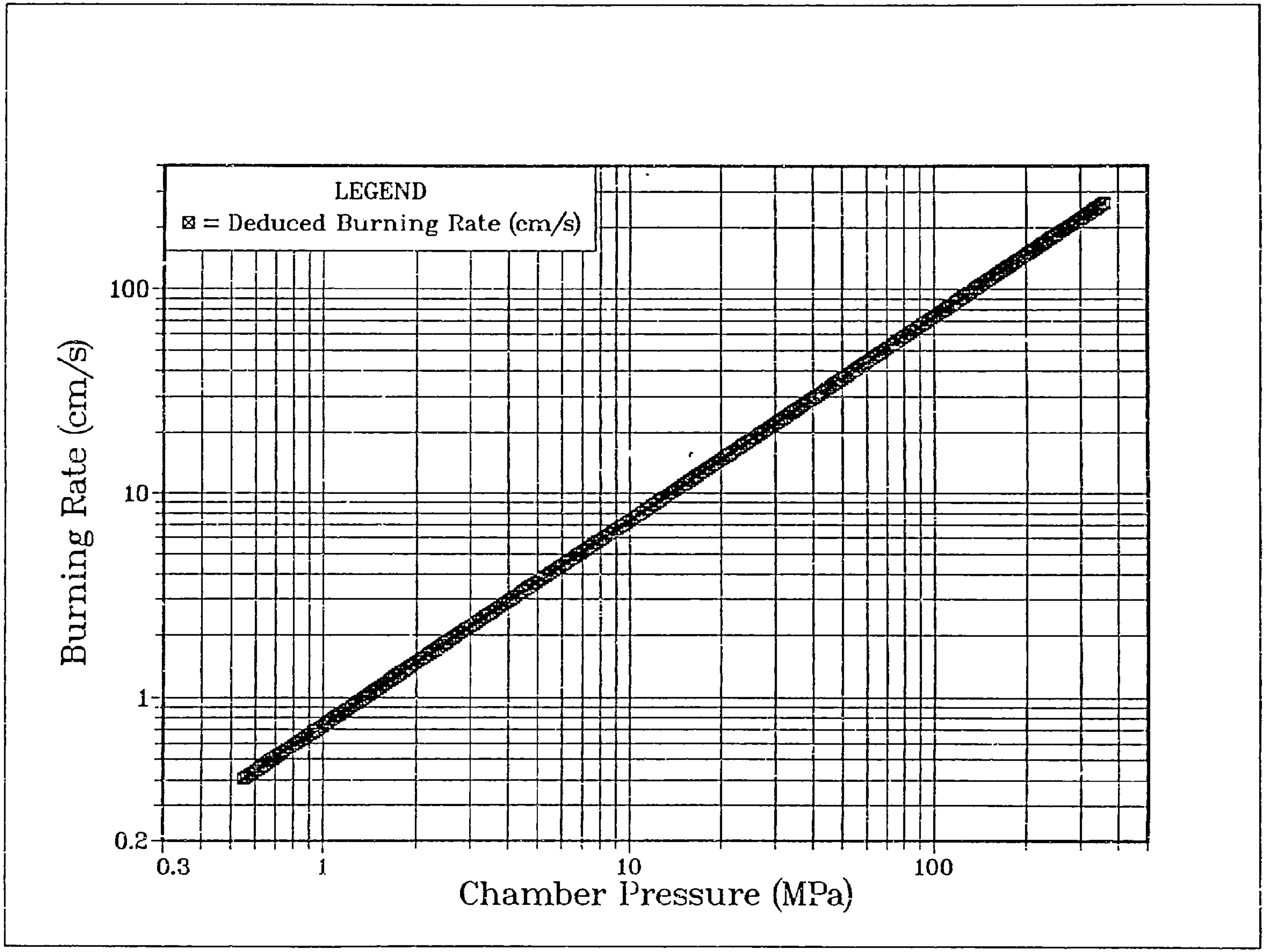

Figure 25. Deduced burning rate, test case 1.

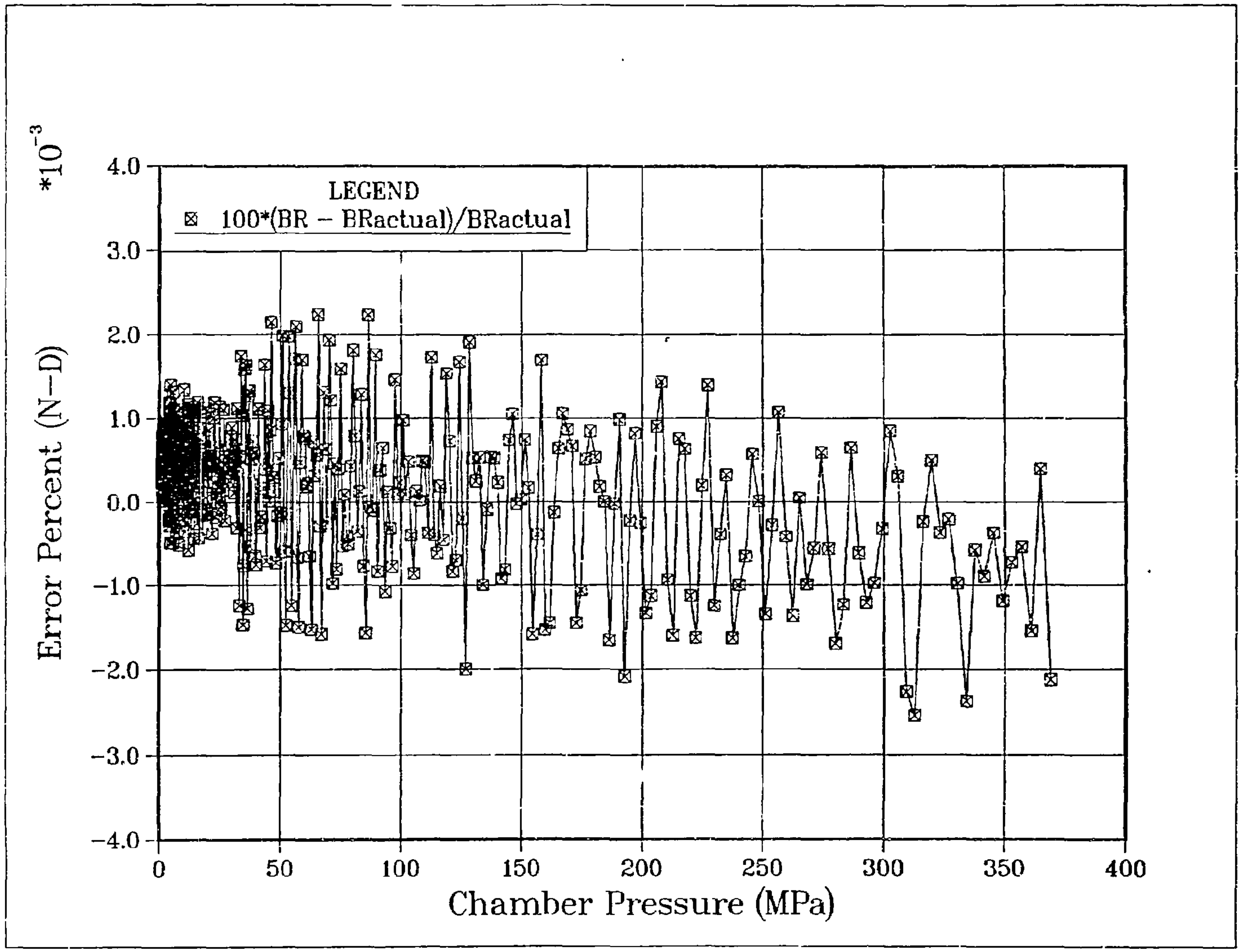

Figure 26. Percent error between BRLCB deduced burn rate and assumed burning rate, test case 1.

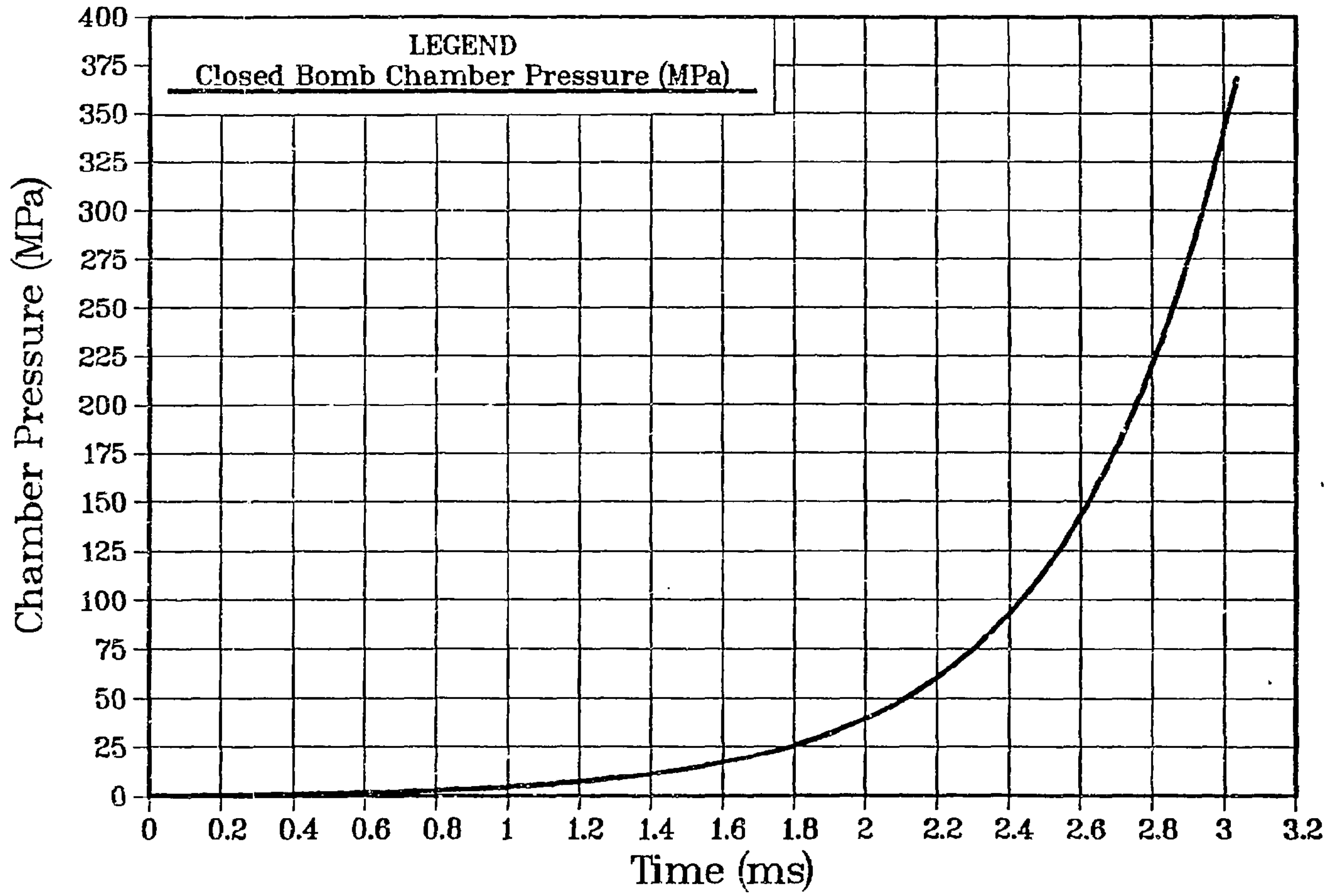

Figure 27. Pressure-time trace generated by BRLCB using input data from the analytic Robbins and Lynn case, test case 2.

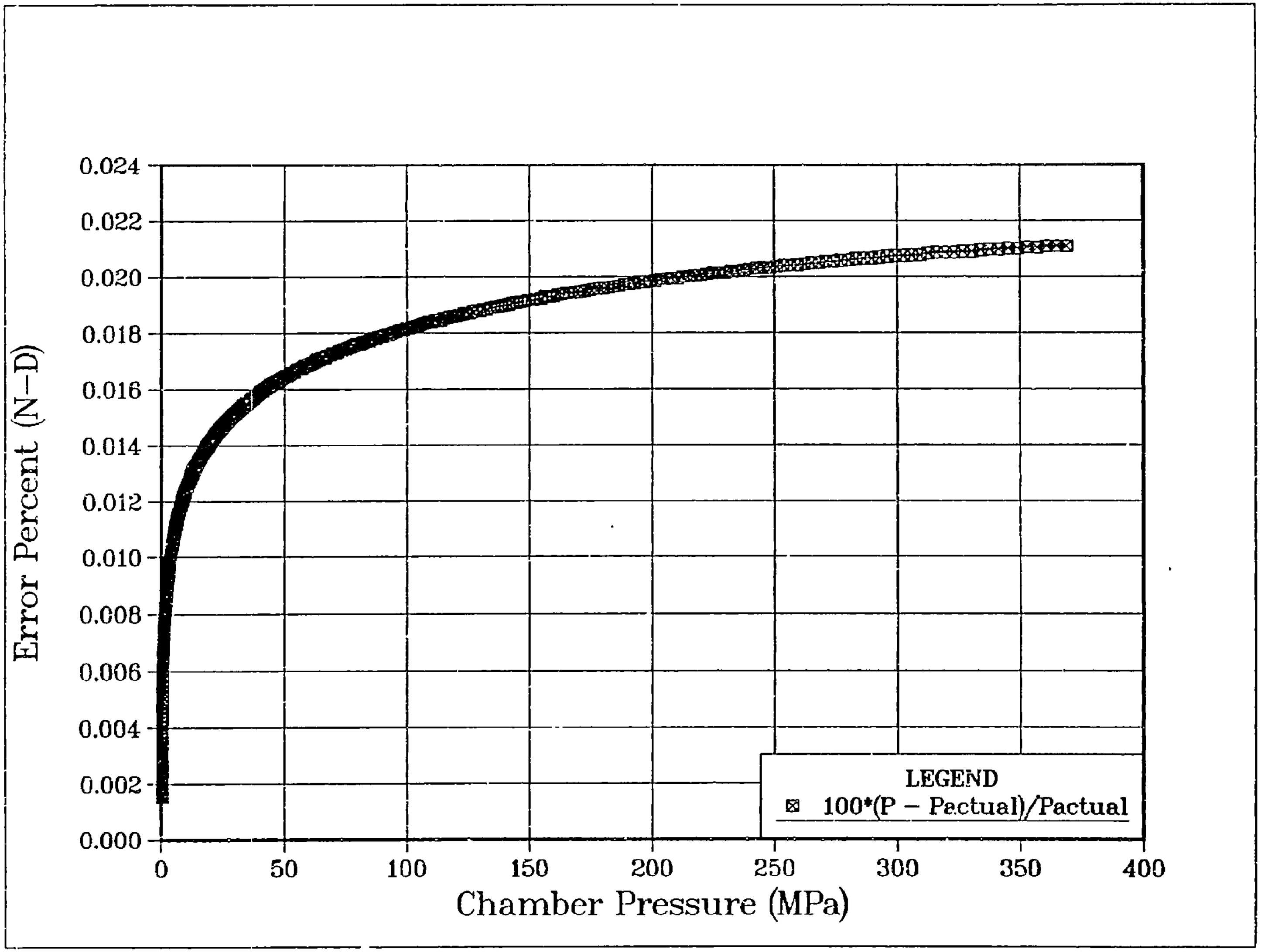

Figure 28. Percent error between BRLCB generated pressure and the analytically generated pressure, test case 2.

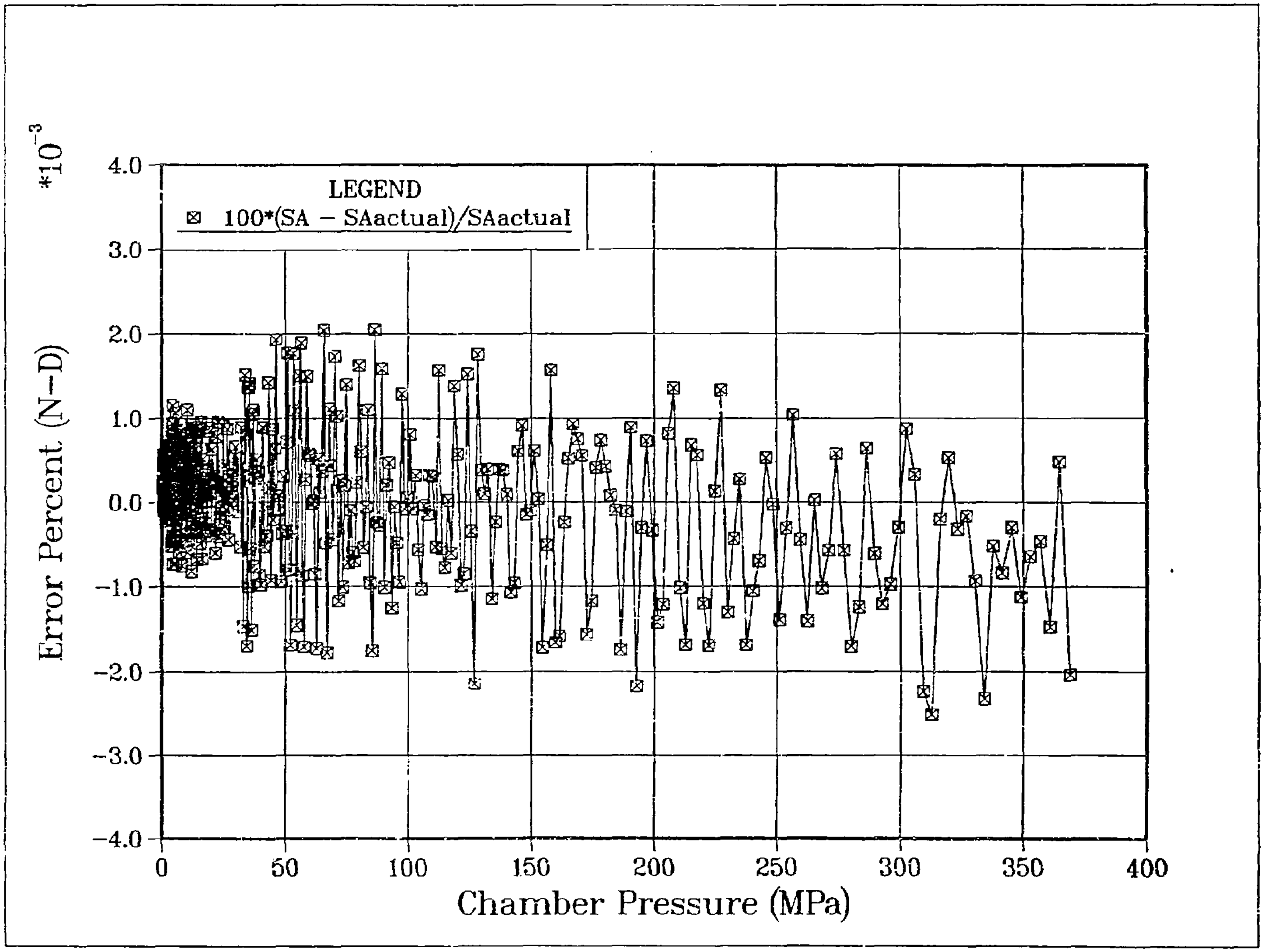

Figure 29. Percent error between BRLCB generated surface area and the analytically generated surface area, test case 3.

The authors believe that the results of these three test cases sufficiently validate the computer implementation of the mathematical model described in section 3 of this report (except for the ETC option). Although the Robbins and Lynn analytic data are for a homogeneous single layered grain, BRLCB utilized the same algorithm in dealing with multilayered grains as for single layer grains. Thus, the BRLCB analysis for multilayered grains should be as accurate as for the single layer gains. The only question for the multilayered grains should be the codes ability to handle the possible jump discontinuities in physical properties associated with going from one layer to the next. At most, any affect due to the discontinuities should be observed only in those time steps which require burning in two distinct layers. However, as will be shown in section 4.5, BRLCB is able to accurately handle the discontinuous jumps between grain layers.

4.2 Series II Test Cases. The three test cases presented in Section 4.1 were run on a CRAY computer with 16 significant figures for the pressure input data. Unfortunately, experimental data seldom are this accurate. Thus, it was of interest to determine the affect less accuracy in input pressure data would have on the computed burning rates. These results are presented in test cases 4 and 5.

Test Case 4. This test case is identical to test case 1 except that the accuracy of the pressure data was reduced from 16 significant figures to 6. The percent error in the computed burning rates is shown in Figure 30.

As can be seen in Figure 30, the maximum percent error is approximately 0.03%. This represents an order of magnitude increase in percent error over the 0.002% observed when the pressure was accurate to 16 significant figures (Figure 26).

Test Case 5. In this test case, the accuracy of the input pressure data was further reduced to four significant figures. As shown in Figure 31, the maximum percent error has risen to between 3% and 4%.

4.3 Series III Test Cases. The objective of the test cases in this series is to validate the coding associated with grain geometry form functions (all geometries except the sandwich grain with inhibited sides for which no pressure-time data could be generated). For test series I, the grain geometry was a single-perforated cylinder and the results from that test series confirmed that the form function was correctly implemented for the single-perforated grain. Form functions for 11 of the remaining 12 grain geometries available in BRLCB will be validated in this series by performing a burning rate reduction

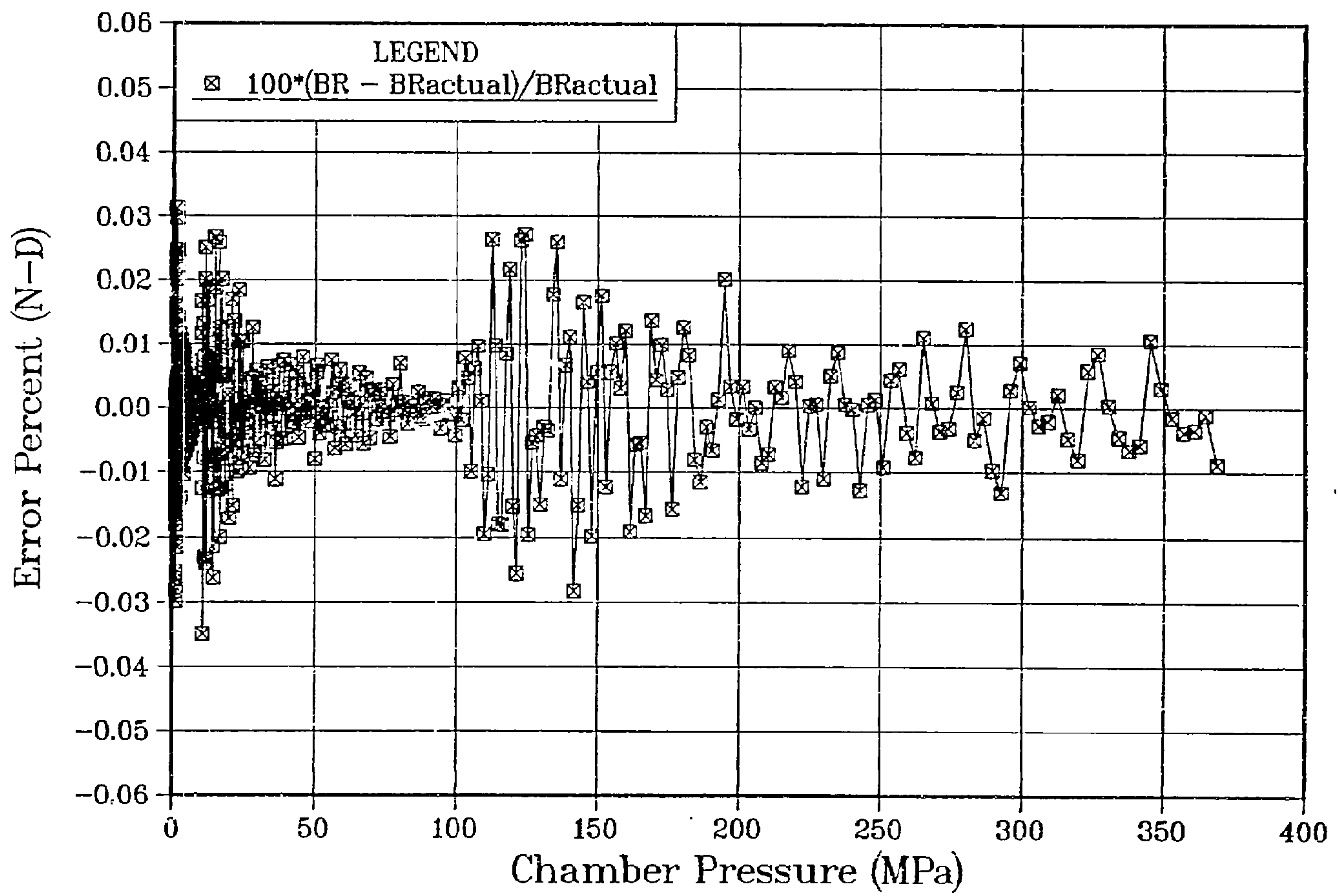

Figure 30. Percent error between BRLCB deduced burning rate and assumed burning rate for pressure data with six significant figures of accuracy, test case 4.

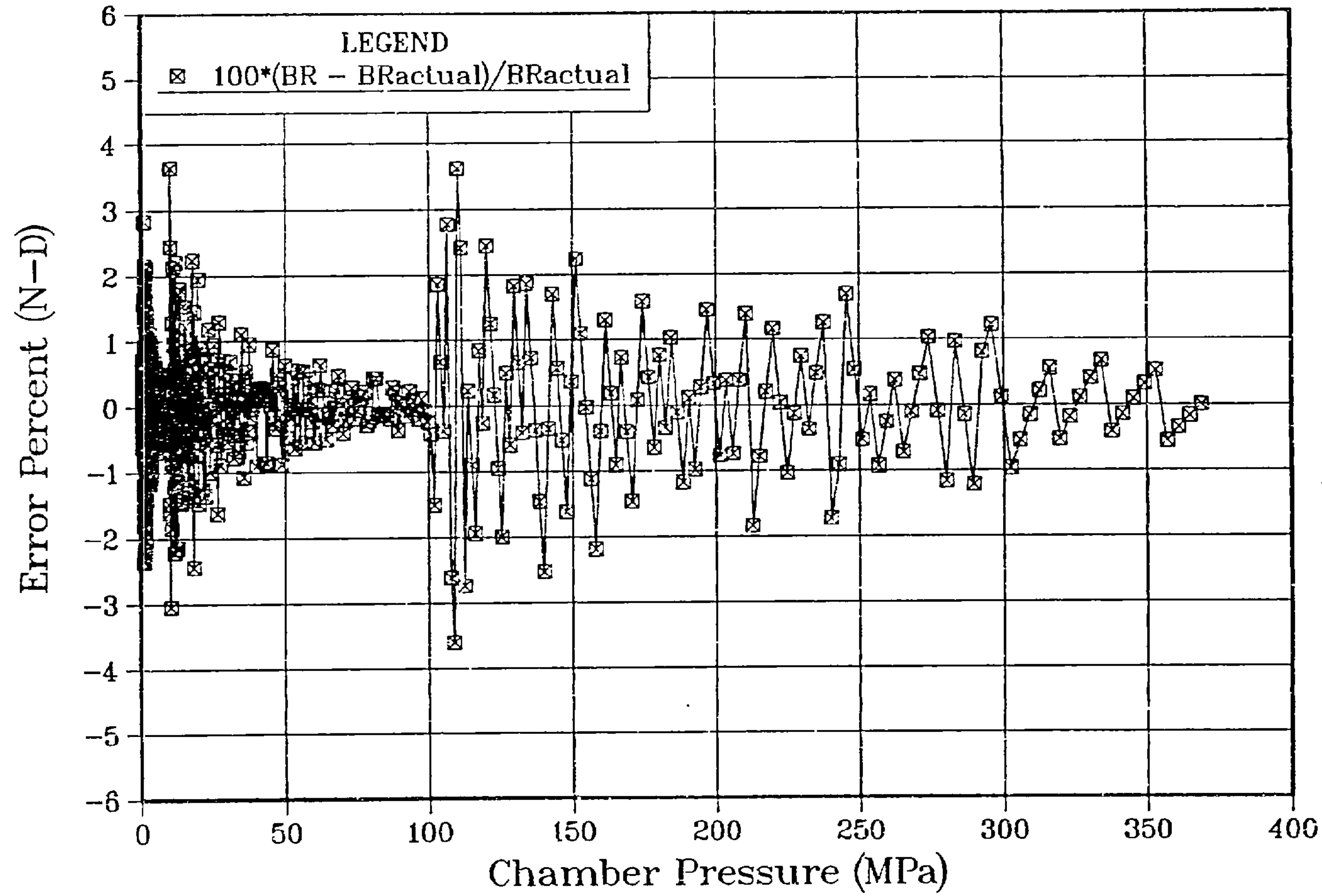

Figure 31. Percent error between BRLCB deduced burning rate and assumed burning rate for pressure data with four significant figures of accuracy, test case 5.

using BRLCB. However, unlike test series I, pressure-time data are not provided by an analytic solution but by adapting the interior ballistic code IBHVG2 (Anderson and Fickie 1987) to simulate a closed-chamber firing. Thus, the pressure-time input data will contain round-off/truncation error which may affect the accuracy of the BRLCB burn rate computation (i.e., increase in percent error between deduced and assumed burn rate). In addition, the IBHVG2 pressure-time data are accurate to only four decimal places (five total decimal digits). Therefore, based upon results of test series II and potential round-off/truncation errors within the pressure data, percent errors between deduced and assumed burn rates on the order of several percent should be expected from the computations.

Test Case 6. For the spherical form function, the percent error between deduced and assumed burn rate is shown in Figure 32. Inputs used for this test case are identical to those of the sample test case provided in section 2.

Test Cases 7–15. Results for the remaining grain geometries (except sandwich with inhibited sides) are presented in Figures 33–42. In all cases, the input to IBHVG2 and BRLCB remained the same except for the grain geometry. These fixed inputs are provided in Table 39.

Table 39. Fixed Input Parameters for IBHVG2 and BRLCB Simulations

Closed-chamber volume:	300 cm^3
Grain geometry:	Varied
Propellant:	
Impetus:	1,140 J/g
Flame temperature:	3,410 K
Ratio of specific heats:	1.225
Molecular weight:	24.869
Covolume:	.996 cm^3/g
Density:	1.58 g/cm^3
Total mass:	90 g + 1 g igniter
Burn rate law:	
	$r = .16\ P^{.908}$ cm/s

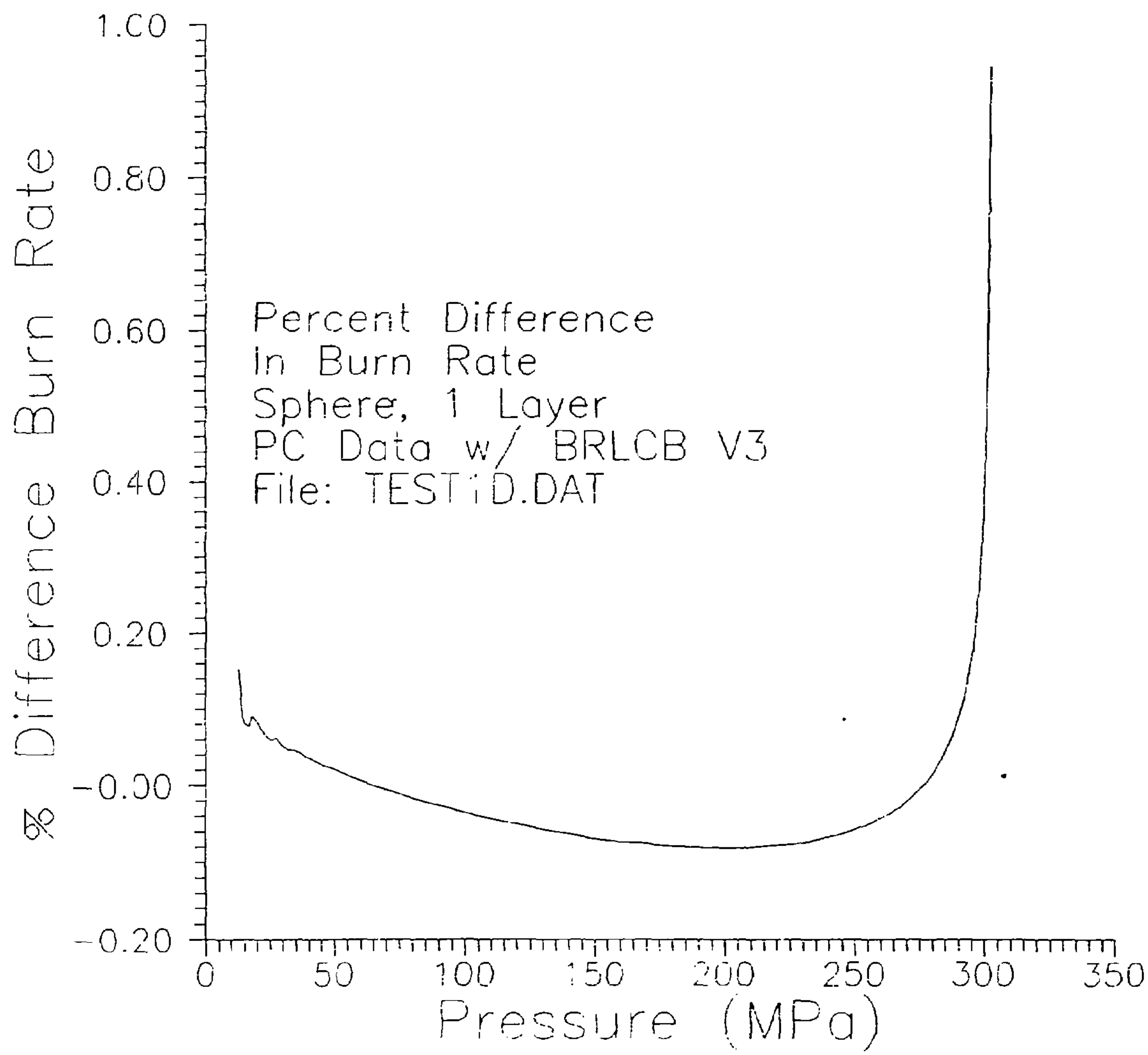

Figure 32. Percent error between BRLCB deduced burn rate and assumed burning rate, spherical grain geometry, test case 6.

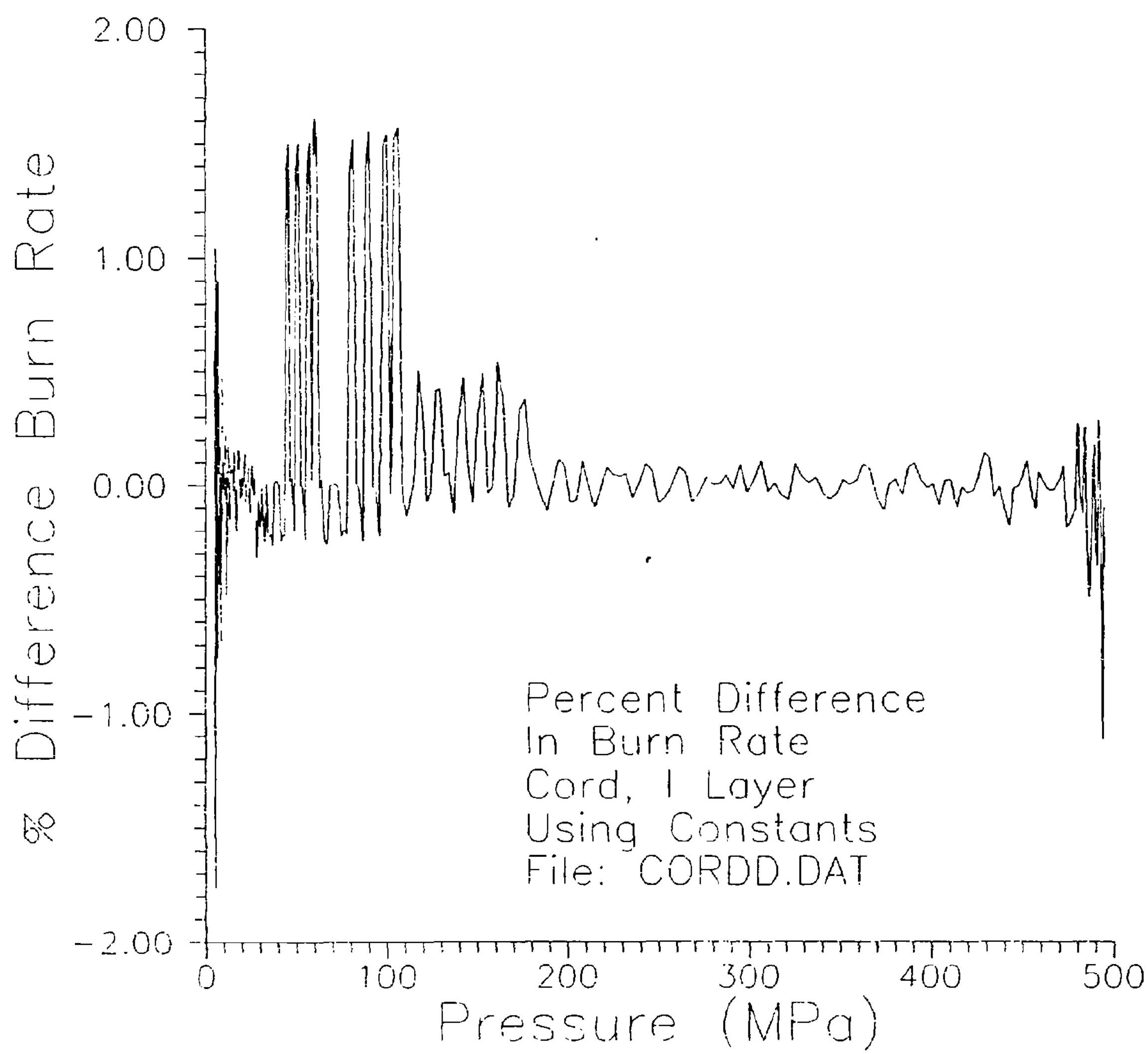

Figure 33. Percent error between BRLCB deduced burn rate and assumed burning rate, cord grain geometry, test case 7.

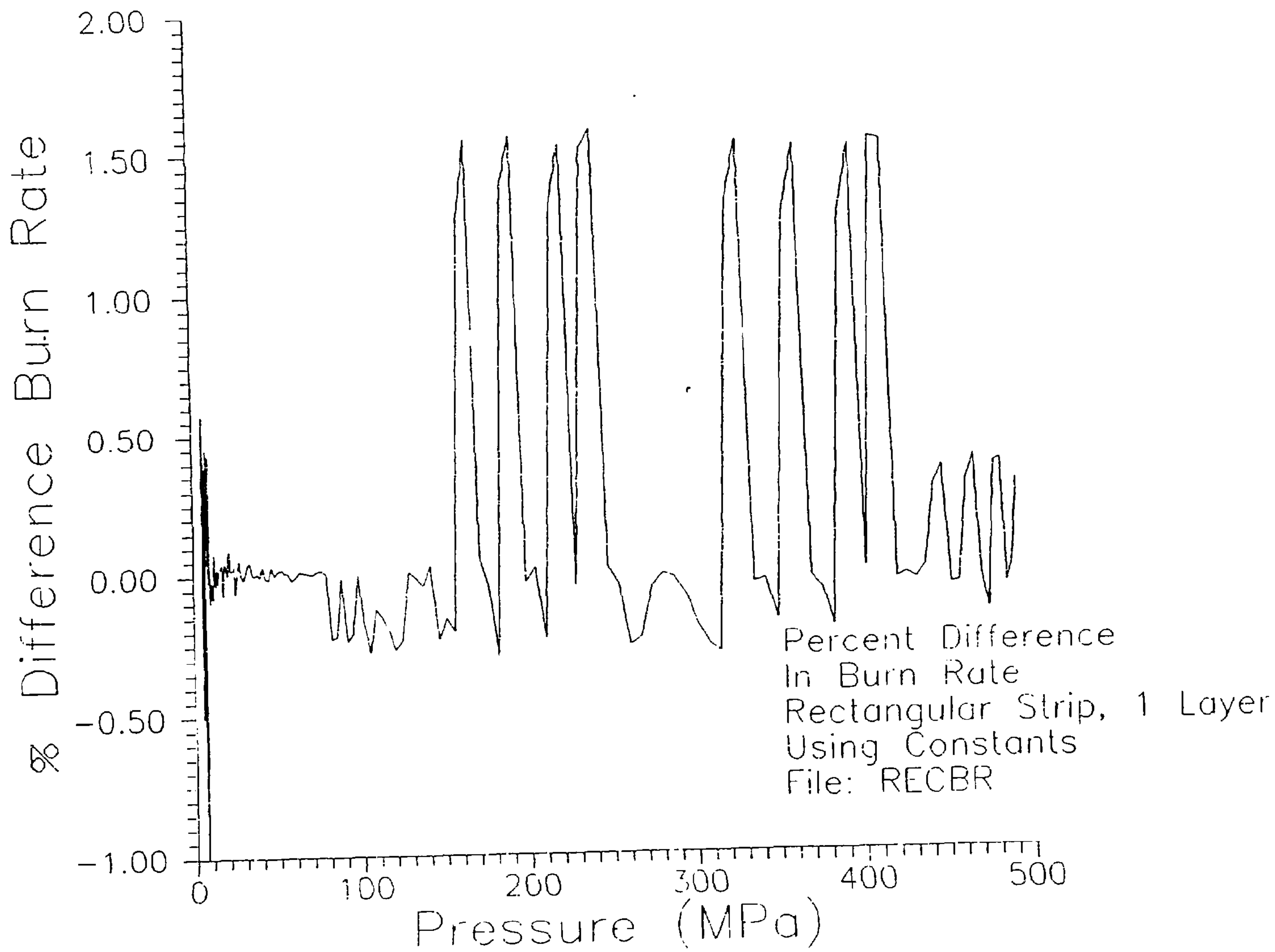

Figure 34. Percent error between BRLCB deduced burn rate and assumed burning rate, rectangular strip grain geometry, test case 8.

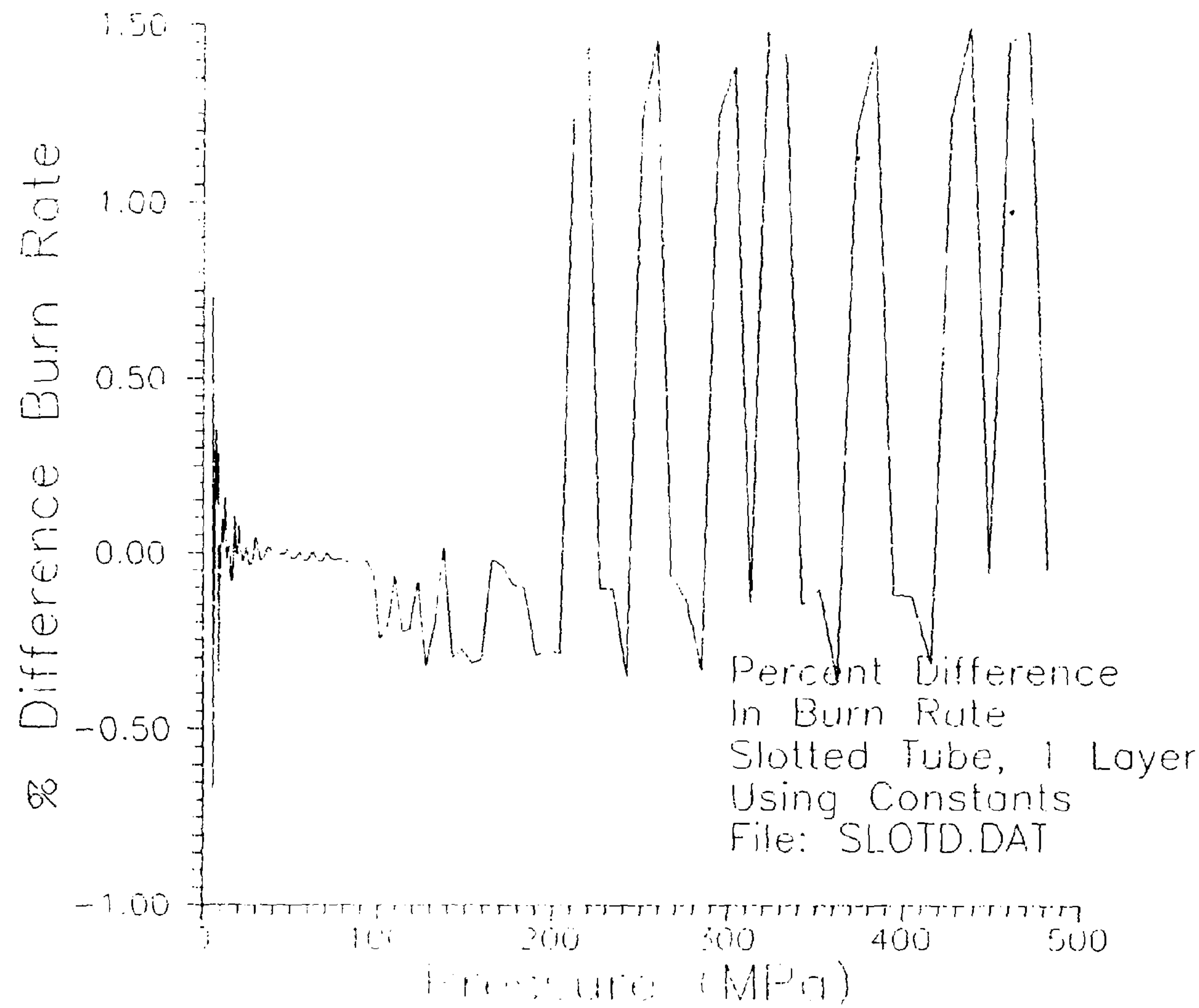

Figure 35. Percent error between BRLCB deduced burn rate and assumed burning rate, slotted tube grain geometry, test case 9.

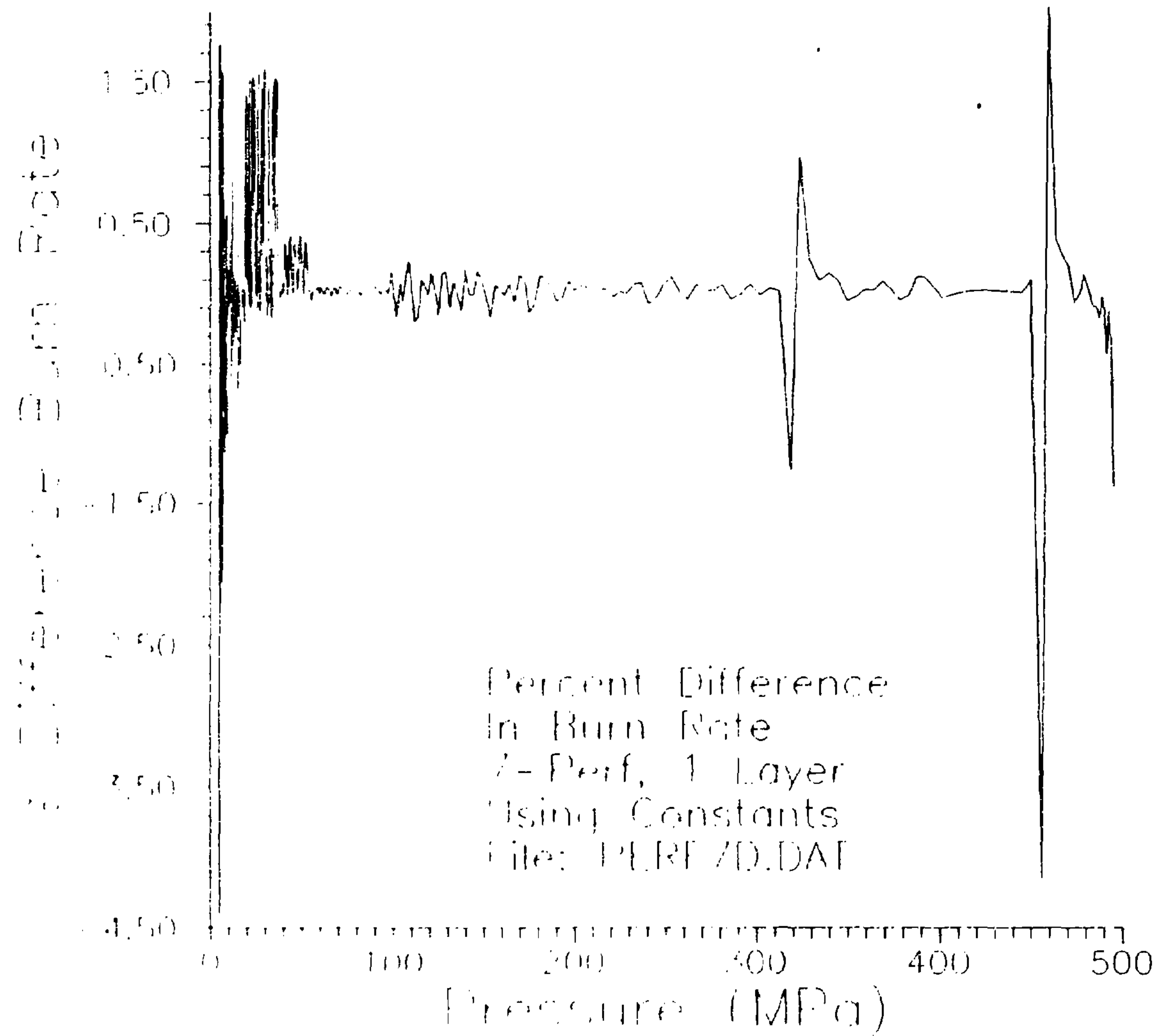

Figure 36. Percent error between BRLCB deduced burn rate and assumed burning rate, 7-perforation grain geometry, test case 10.

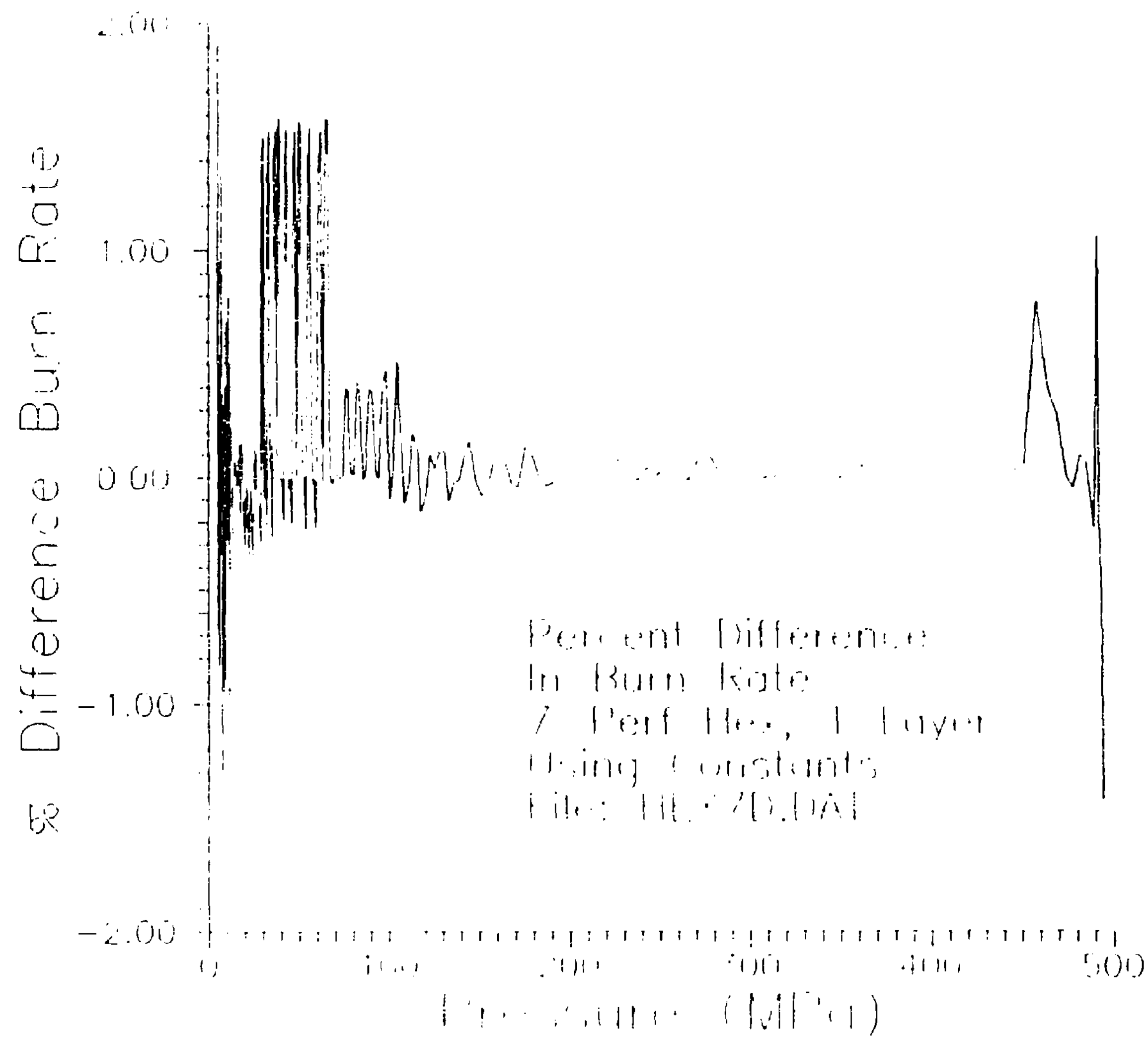

Figure 37. Percent error between BRLCB deduced burn rate and assumed burning rate, 7-perforation hex grain geometry, test case 11.

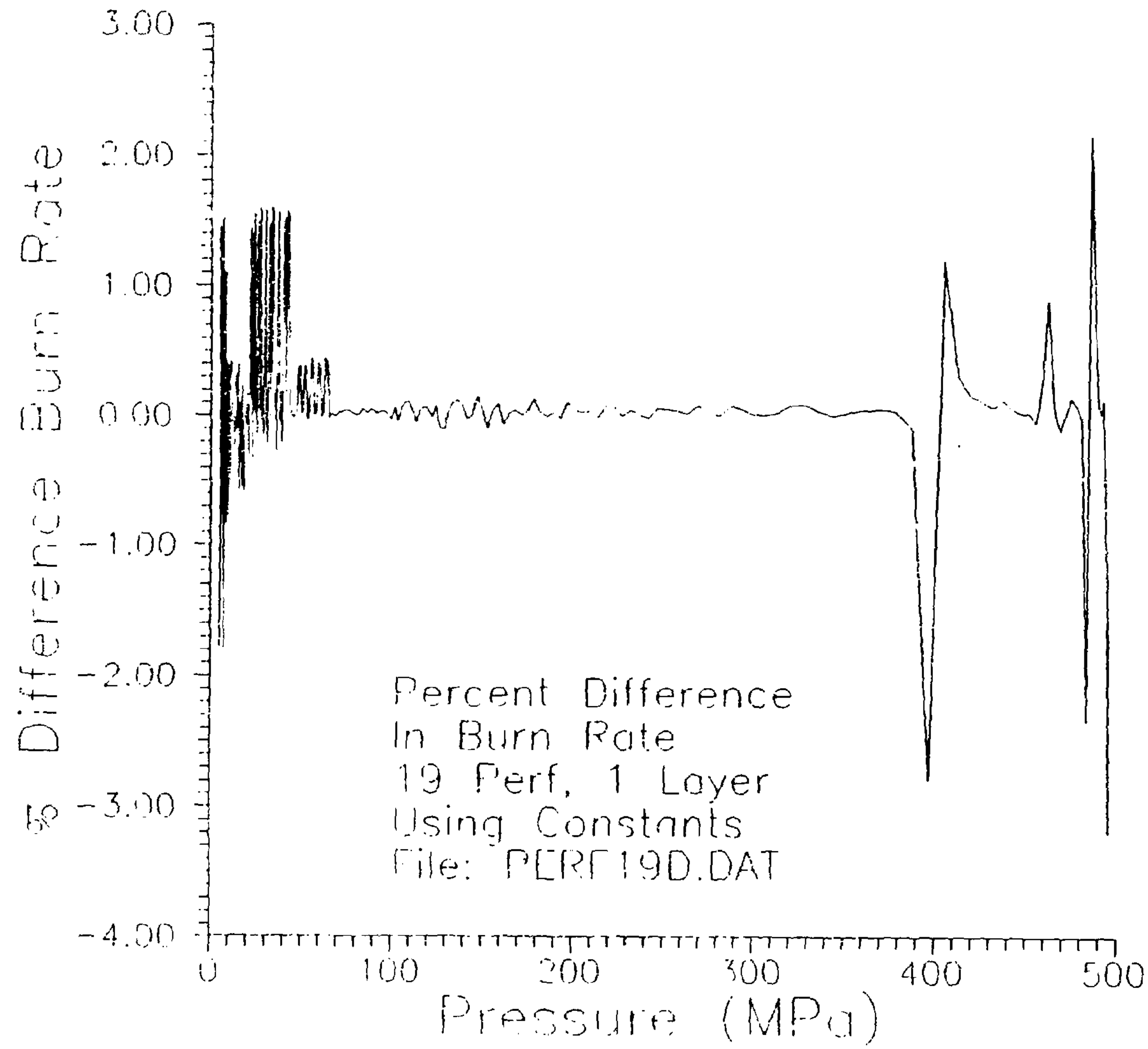

Figure 38. Percent error between BRLCB deduced burn rate and assumed burning rate, 19-perforation grain geometry, test case 12.

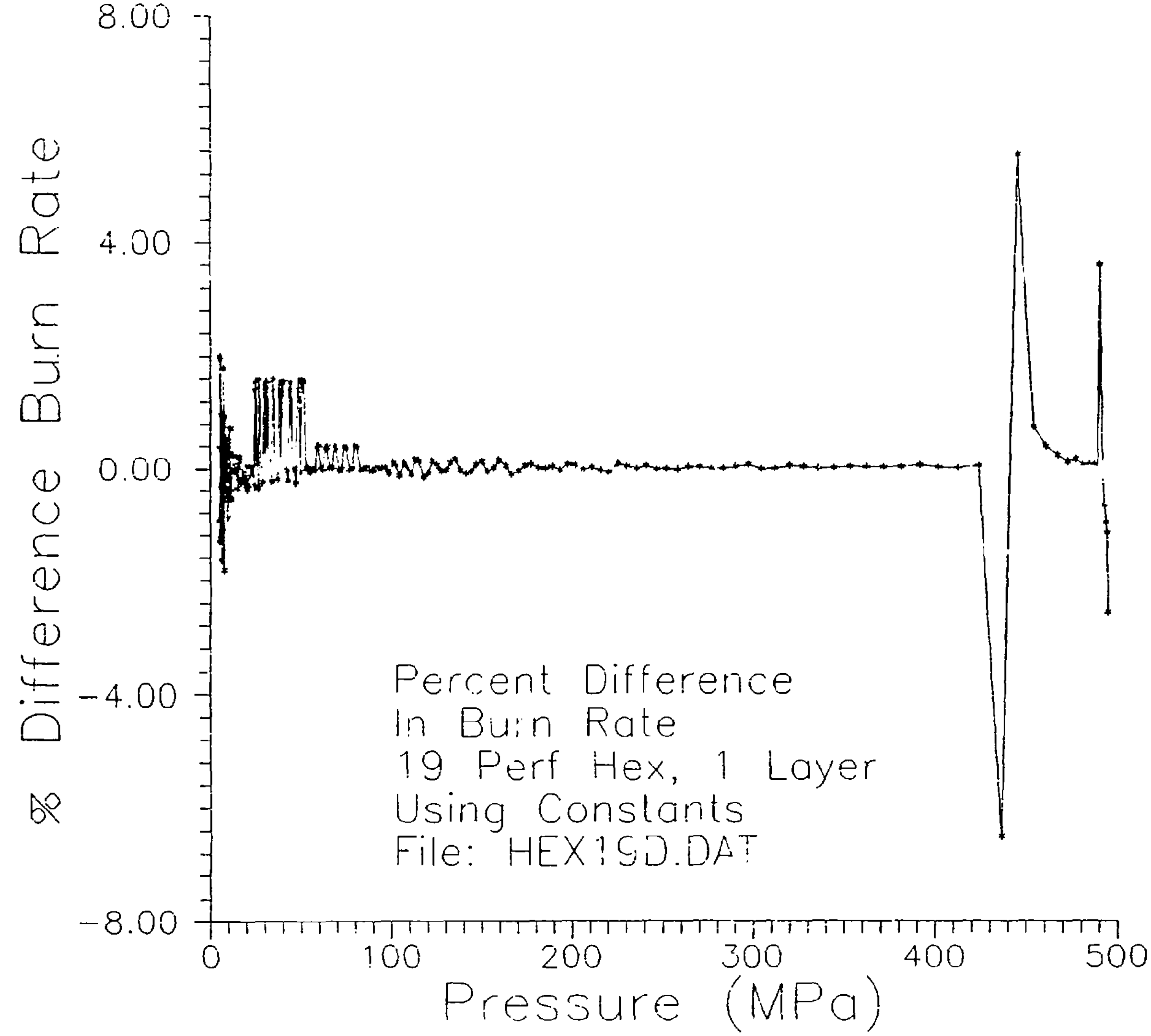

Figure 39. Percent error between BRLCB deduced burn rate and assumed burning rate, 19-perforation hex grain geometry, test case 13.

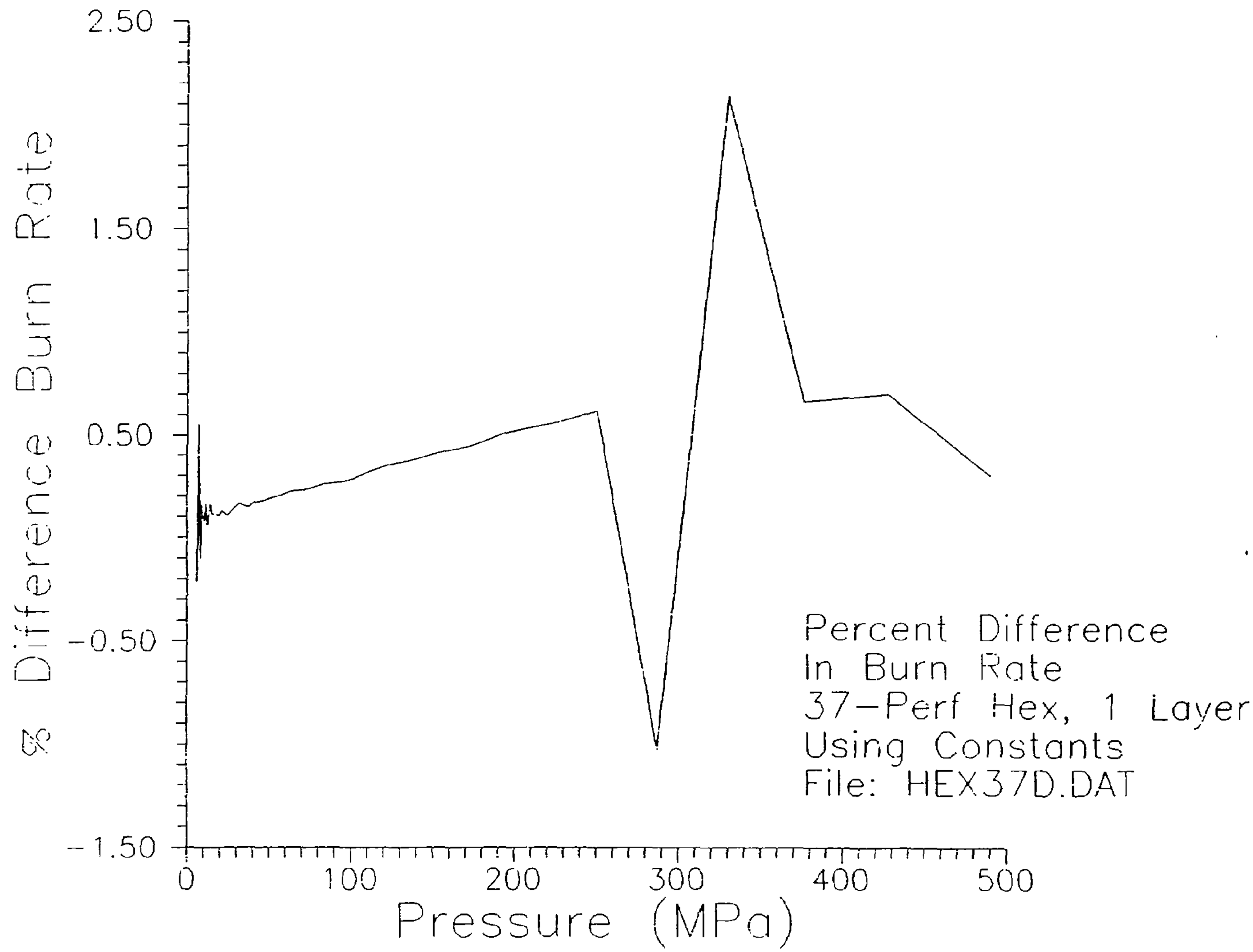

Figure 40. Percent error between BRLCB deduced burn rate and assumed burning rate, 37-perforation grain geometry, test case 14.

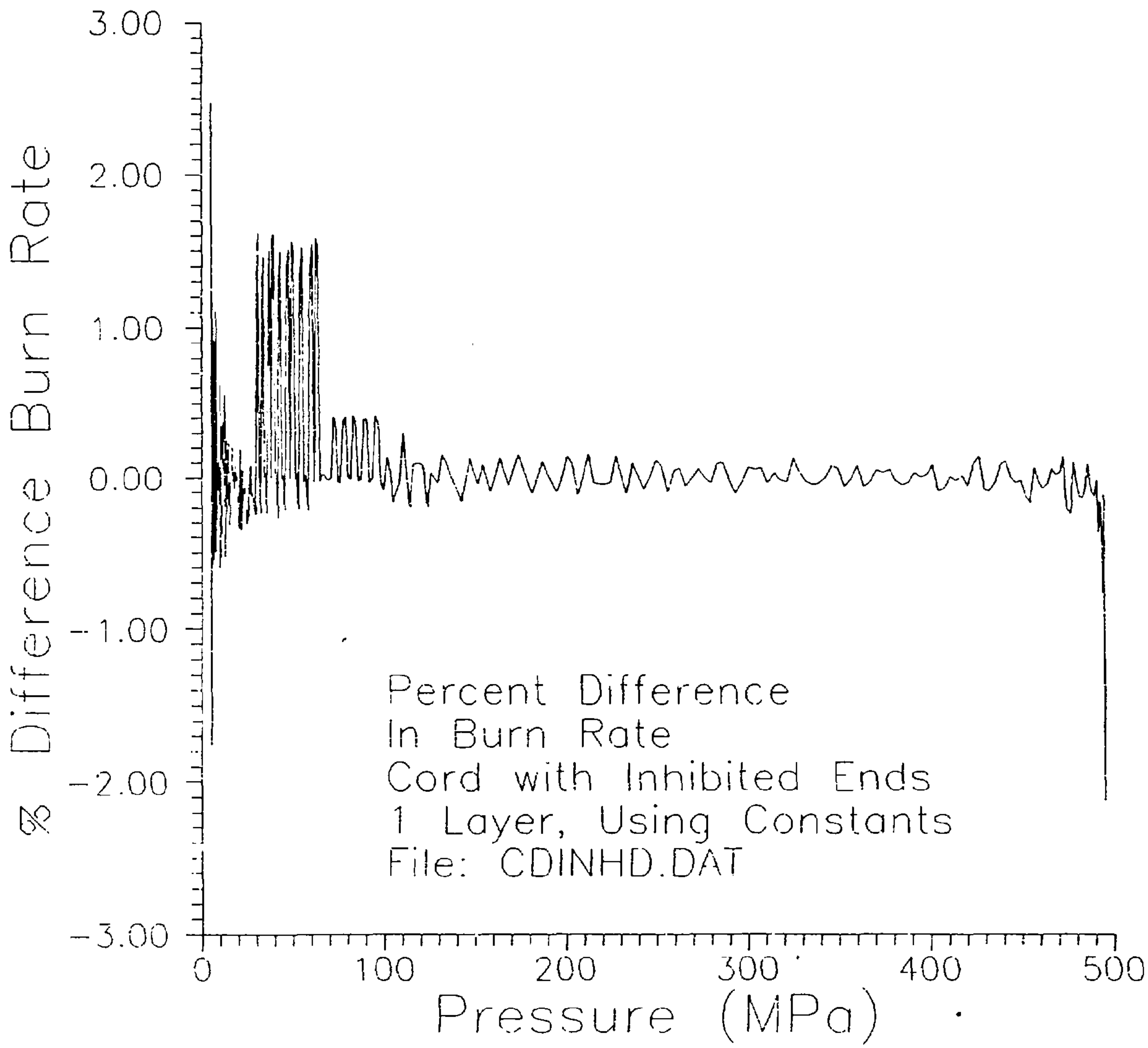

Figure 41. Percent error between BRLCB deduced burn rate and assumed burning rate, cord with inhibited ends grain geometry, test case 15.

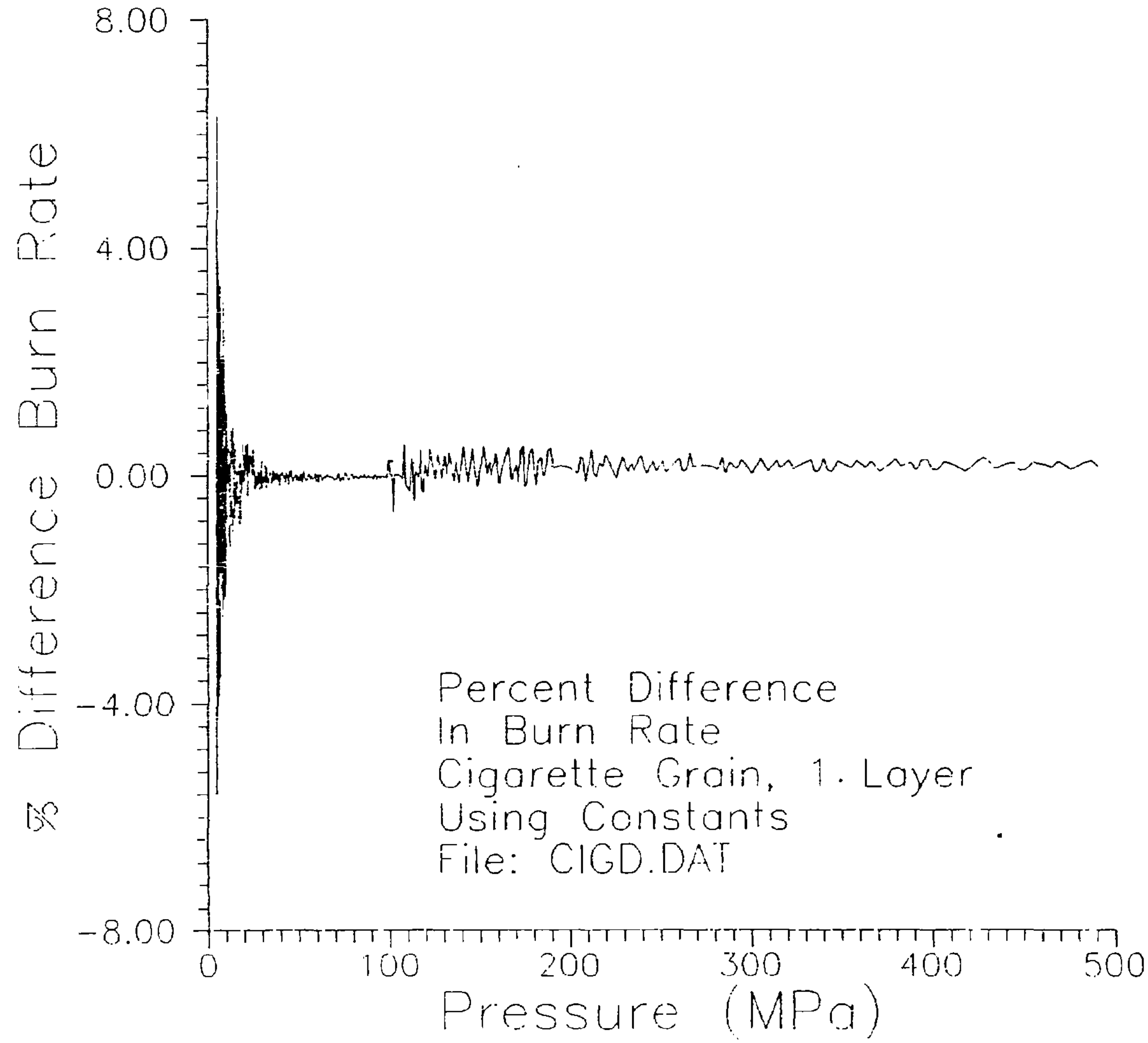

Figure 42. Percent error between BRLCB deduced burn rate and assumed burning rate, cigarette grain geometry, test case 16.

As can be observed from Figures 32 through 42, the percent error from the BRLCB calculations is generally within the 2–3% expected. The exceptions being the 19-perforation hex grain and the cigarette grain. However, as shown in Figure 39 where the actual data points are starred, the percent error is outside of the expected range for only two points. In the case of the 19-perforation hex grain, these points correspond to a grain slivering event; for the cigarette grain, the points are the first two points in the calculation where the numerical methods utilized will be most inaccurate. Based upon the results of this test series, the authors believe that the grain geometry form functions have been correctly implemented.

4.4 <u>Series IV Test Case</u>. Test Case 17. The objective of this series was to validate the BRLCB ETC burn rate reduction option. The ETC option is implemented in the mathematical model by assuming that the electrical energy is strictly additive with the chemical energy. Thus, the electrical energy simply represents a source term to the energy balance equation. As in the series III test cases, input data were generated using an interior ballistic code. In this case, a modified version of IBHVG2 (Earnhart and Winsor 1992) capable of simulating the ETC process. Inputs for the modified IBHVG2 simulation and BRLCB reduction are provided in Table 40.

Table 40. Input Parameters for IBHVG2 and BRLCB Simulations for ETC Burn Rate Reduction

Closed-chamber volume:	65.5 cm^3
Grain geometry:	Sphere
Propellant:	
Impetus:	1,165 J/g
Flame temperature:	3,680 K
Ratio of specific heats:	1.2155
Molecular weight:	26.2532
Covolume:	.996 cm^3/g
Density:	1.6 g/cm^3
Total mass:	13 g + .5 g igniter
Burn rate law:	
	$r = .2259\ P^{.863}$ cm/s

The electrical energy added to the system is shown in Figure 43.

Percent error between deduced and assumed burn rate is given in Figure 44. As shown in the figure, the percent error is well within the expected limits. Thus, the authors feel the ETC burn rate reduction option is properly implemented.

4.5 Series V Test Cases. In this series, the ability of BRLCB to handle layered propellants with constant and varying properties is investigated. Test case 18 addresses constant properties, while varying properties are investigated in test case 19. Unlike the previous test cases, these two test cases use the pressure generation option of BRLCB to generate the pressure data used in the burn rate reduction. Although this may appear to represent a circular validation, this is not the case. The object of these test cases is to determine if BRLCB can cleanly handle the potential discontinuous jumps in properties (thermochemical and burn rate) at the layer boundaries. The pressure generation option of BRLCB produces a pressure history at equal time steps, the jump between layers does not necessarily occur at one of these time steps. Therefore, the pressure history generated by BRLCB "smears" the jump between layers across one time step and provides no additional information to the burn rate reduction option that would not be available from an experimental closed-chamber firing.

Test Case 18. In this test case, a five-layer sphere with constant properties in each layer is investigated. Input information is provided in Table 41.

The assumed burn rates used in this case are shown in Figure 45. The corresponding pressure-time data generated by BRLCB are shown in Figure 46.

Results of the BRLCB calculation are presented in Figures 47 and 48. Figure 47 is the deduced burn rate and Figure 48 the percent error between the deduced and calculated burning rates.

As illustrated in Figure 47, BRLCB is able to cleanly handle the jumps between the layers. The percent error shown in Figure 48 is felt acceptable by the authors, being less than 0.01% for all but the last 10 points

Test Case 19. This test case is similar to test case 18 except that the properties in each layer (except burn rate) are varying as shown in Table 42.

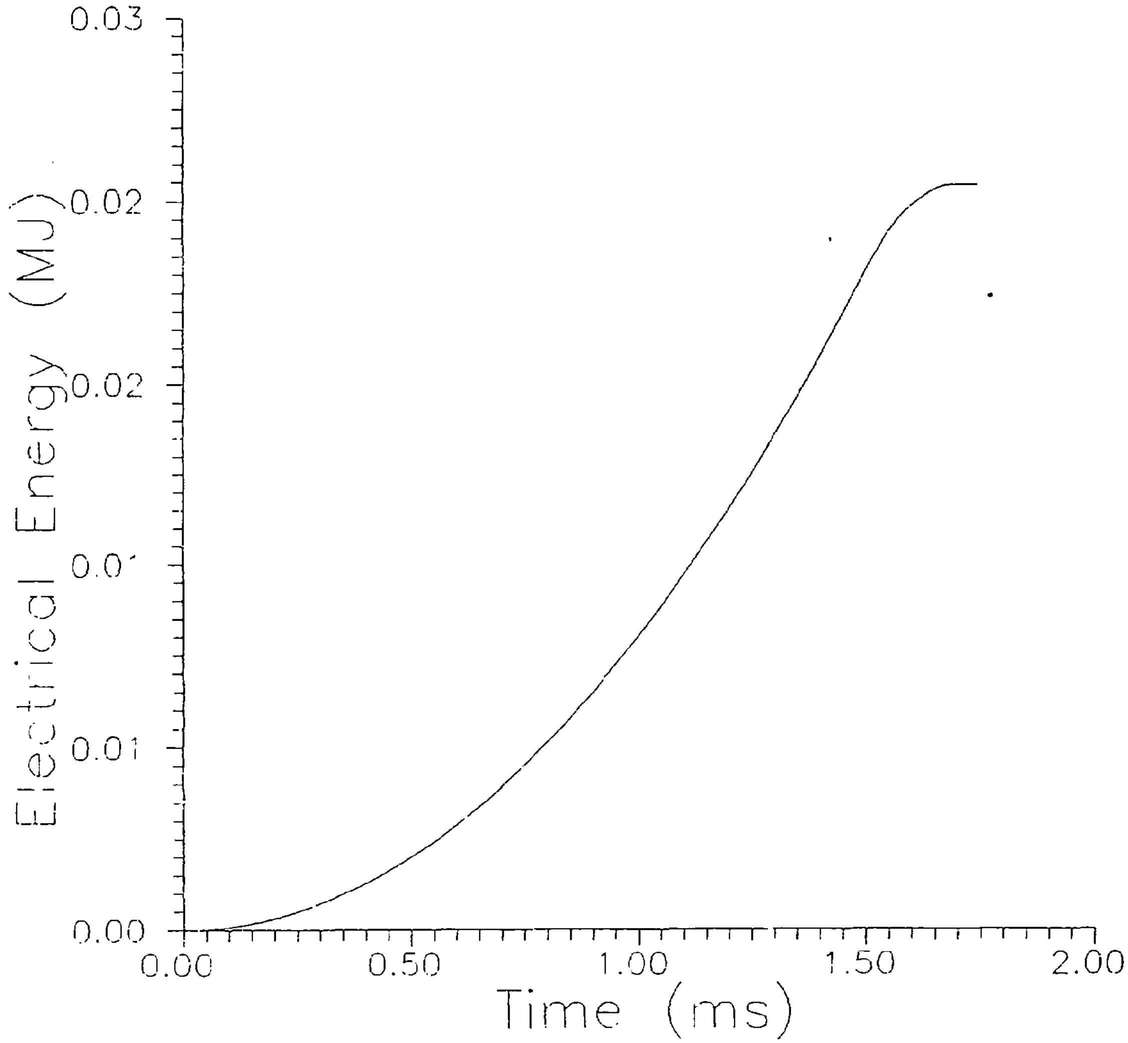

Figure 43. Electrical energy added for ETC closed-chamber IBHVG2 and BRLCB simulations, test case 17.

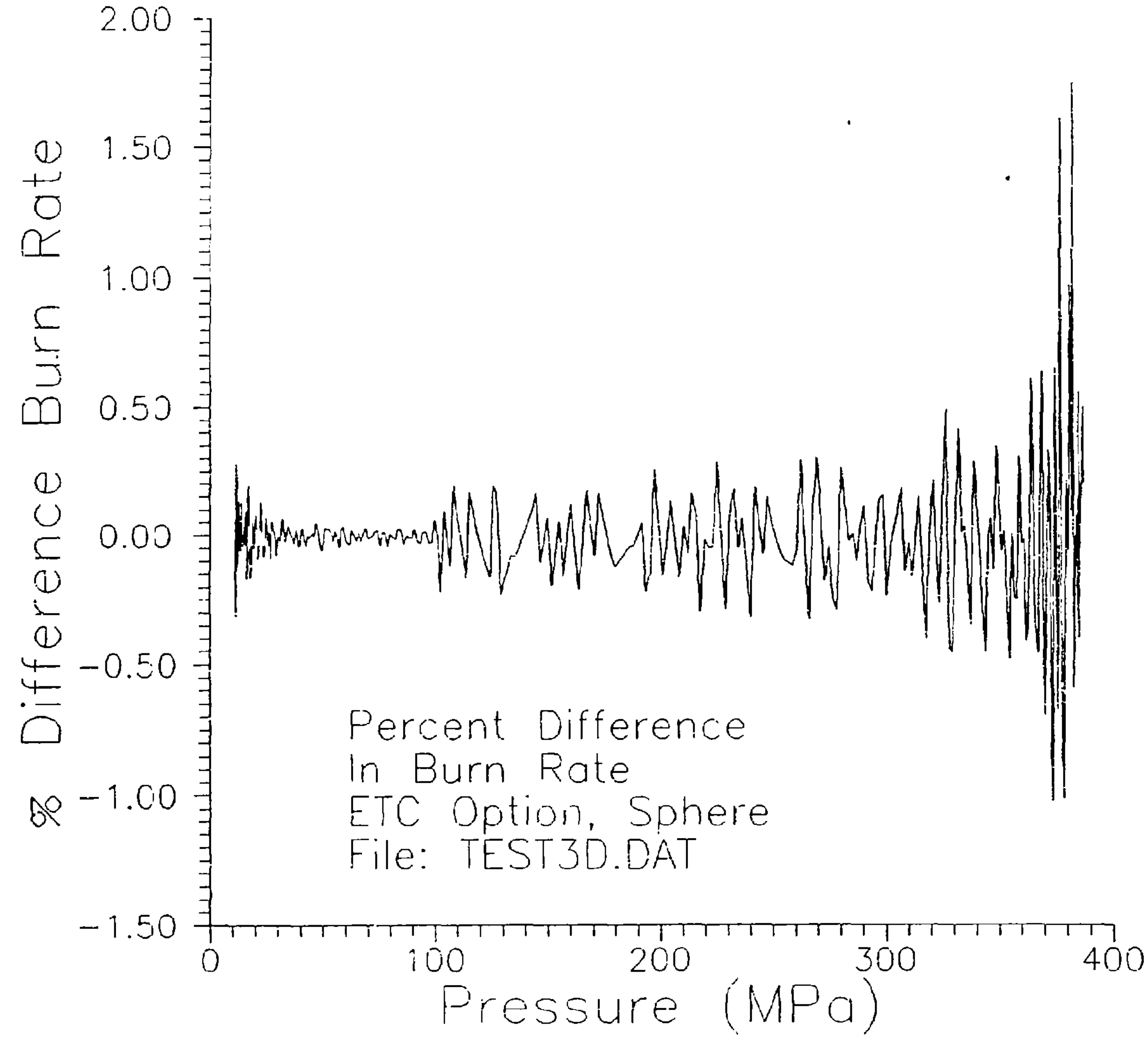

Figure 44. Percent error between BRLCB deduced burn rate and assumed burning rate, test case 17.

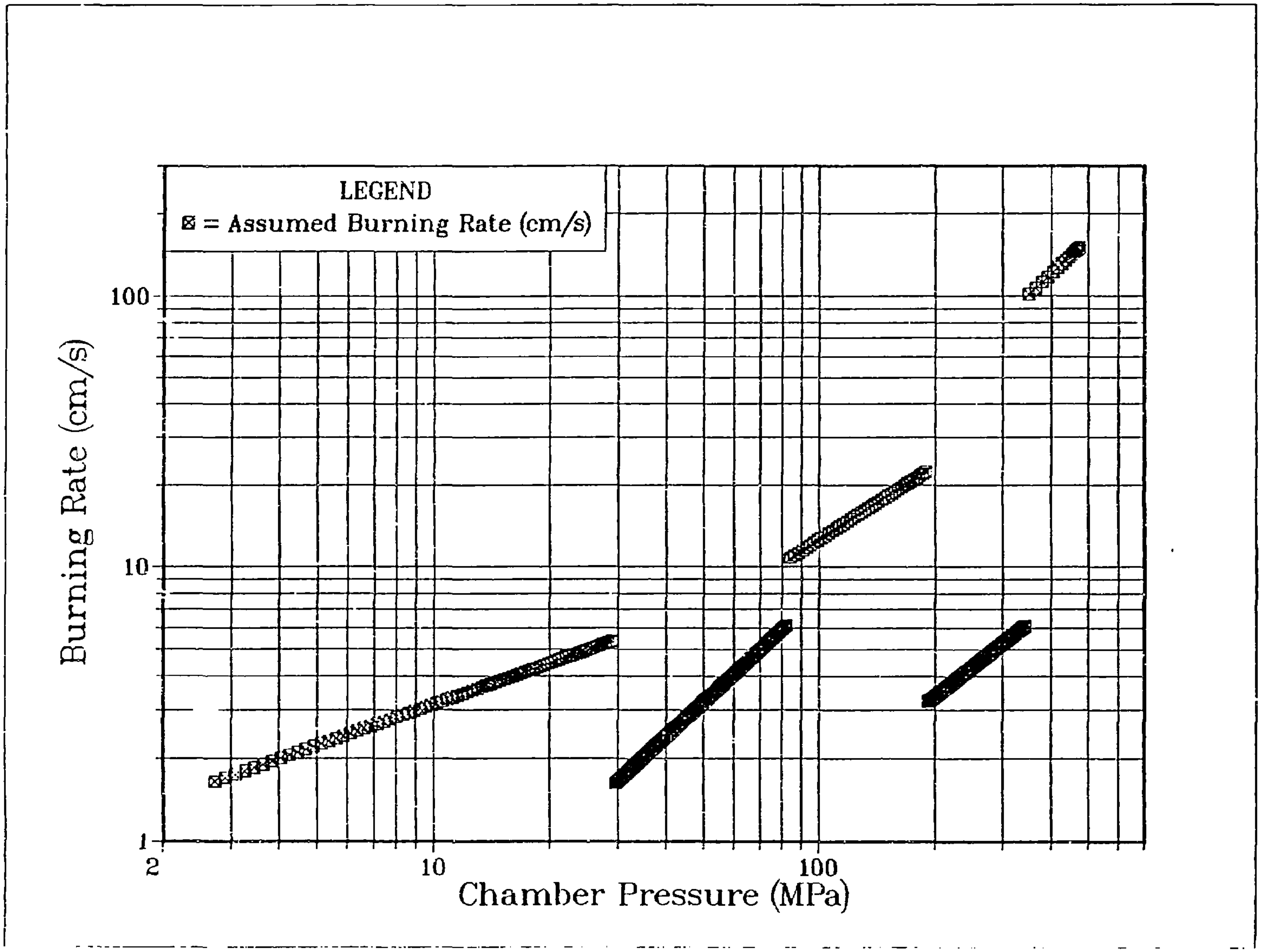

Figure 45. Assumed burn rates for five-layer sphere with constant properties in each layer, test case 18.

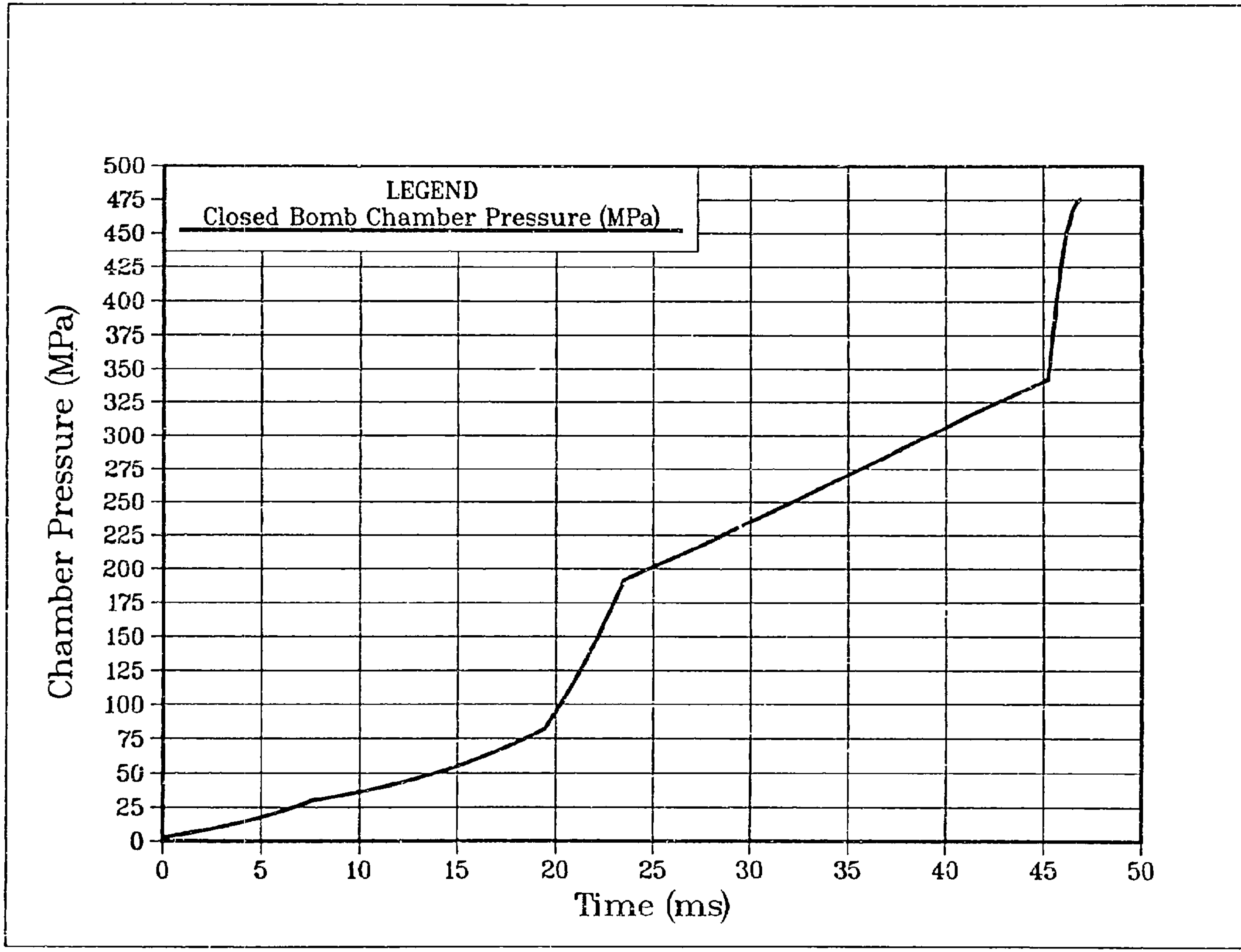

Figure 46. Pressure history generated by BRLCB for five-layer sphere with constant properties in each layer, test case 18.

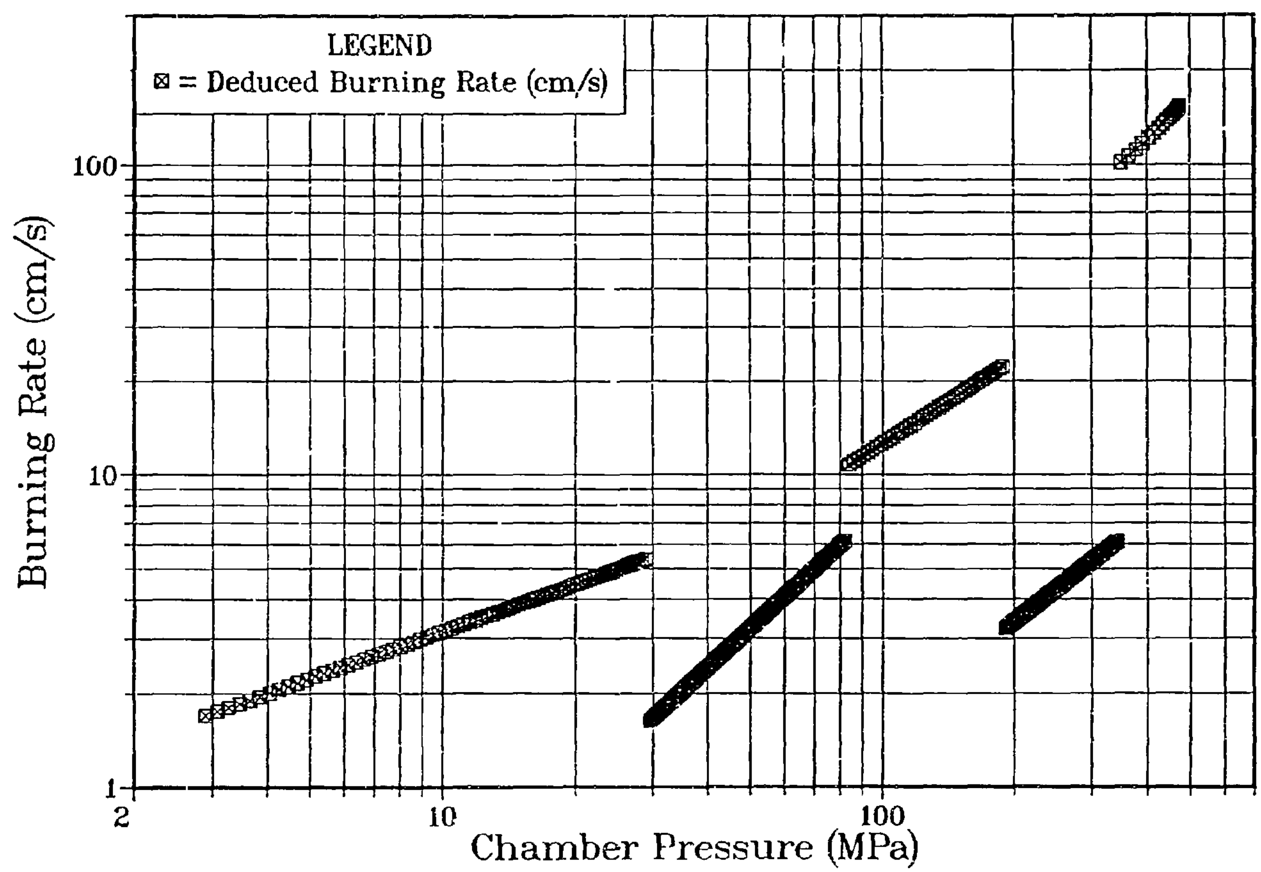

Figure 47. Deduced burning rates for five-layer sphere with constant properties in each layer, test case 18.

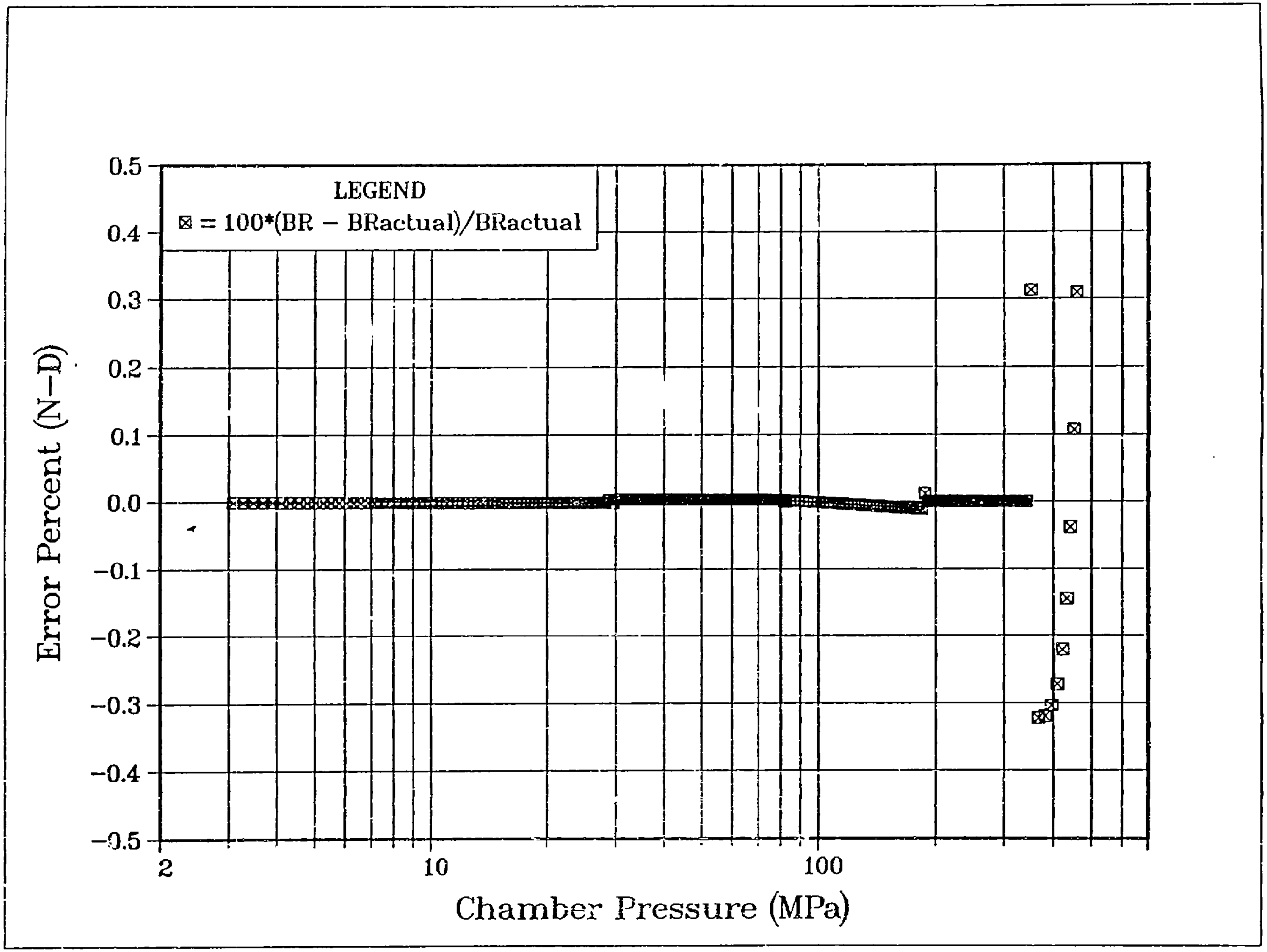

Figure 48. Percent error between BRLCB deduced burn rate and assumed burning rate, five-layer sphere with constant properties in each layer, test case 18.

Table 41. Input Parameters for BRLCB Simulations for Five-Layer Sphere With Constant Properties in Each Layer, Test Case 18

Closed-chamber volume: 300 cm^3					
Grain geometry: sphere (five layers) (.5 cm diameter)					
Starting depth: (cm)	Layer 1 0.0	Layer 2 .0263	Layer 3 .06688	Layer 4 .1316	Layer 5 .23434
Propellant properties:					
Impetus (J/g):	382.5	540.4	803.7	1,064.2	1,398.3
Flame temperature (K):	2,300	2,600	2,900	3,200	3,700
Gamma (–):	1.27	1.26	1.25	1.24	1.22
Molecular weight (–):	50	40	30	25	22
Covolume (cm^3/g:	.95	.92	.89	.85	.80
Density (g/cm^3):	1.4	1.45	1.5	1.55	1.65
Total mass: 110 g + 2 g igniter					
Burn rate law (cm/s):	$r=1.0P^{.5}$	$r=.02P^{1.3}$	$r=.2P^{.9}$	$r+.01P^{1.1}$	$r=.05P^{1.3}$

The assumed burn rates used in this case are shown in Figure 49. The corresponding pressure-time data generated by BRLCB are shown in Figure 50 by the solid line.

Results of the BRLCB calculation are presented in Figures 51 and 52. Figure 51 is the deduced burn rate and Figure 52 the percent error between the deduced and calculated burning rates.

As with the test case 18, Figure 51 indicates that BRLCB is capable of cleanly handling the discontinuous jumps between layers. The percent error shown in Figure 52 is almost identical to that shown in Figure 48 for the 5 layer sphere with constant properties. Thus, the use of the integrals to compute the average of the variable properties appears to have little or no effect on the accuracy of the burn rate calculation compared to having constant property values.

Table 42. Input Parameters for BRLCB Simulations for Five-Layer Sphere With Varying Properties in Each Layer, Test Case 19

Closed-chamber volume: 300 cm^3					
Grain geometry: sphere (five layers) (.5 cm diameter)					
Starting depth: (cm)	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
	0.0	.02636	.06688	.1316	.23434
Propellant properties:					
Impetus (J/g):					
Start:	382.5	540.4	803.7	1,064.2	1,398.3
End:	540.4	803.7	1,064.2	1,398.3	1,398.3
Flame temperature (K):					
Start:	2,300	2,600	2,900	3,200	3,700
End:	2,600	2,900	3,200	3,700	3700
Gamma (–):					
Start:	1.27	1.26	1.25	1.24	1.22
End:	1.26	1.25	1.24	1.22	1.22
Molecular weight (–):					
Start:	50	40	30	25	22
End:	40	30	25	22	22
Covolume (cm^3/g):					
Start:	.95	.92	.89	.85	.80
End:	.92	.89	.85	80	.80
Density (g/cm^3):					
Start:	1.4	1.45	1.5	1.55	1.65
End:	1.45	1.5	1.55	1.65	1.65
Total mass: 110 g + 2 g igniter					
Burn rate law (cm/s):	$4 = 1.0P^{.5}$	$r = .02P^{1.3}$	$r = .2P^{.9}$	$r = .01P^{1.1}$	$r = .05P^{1.3}$

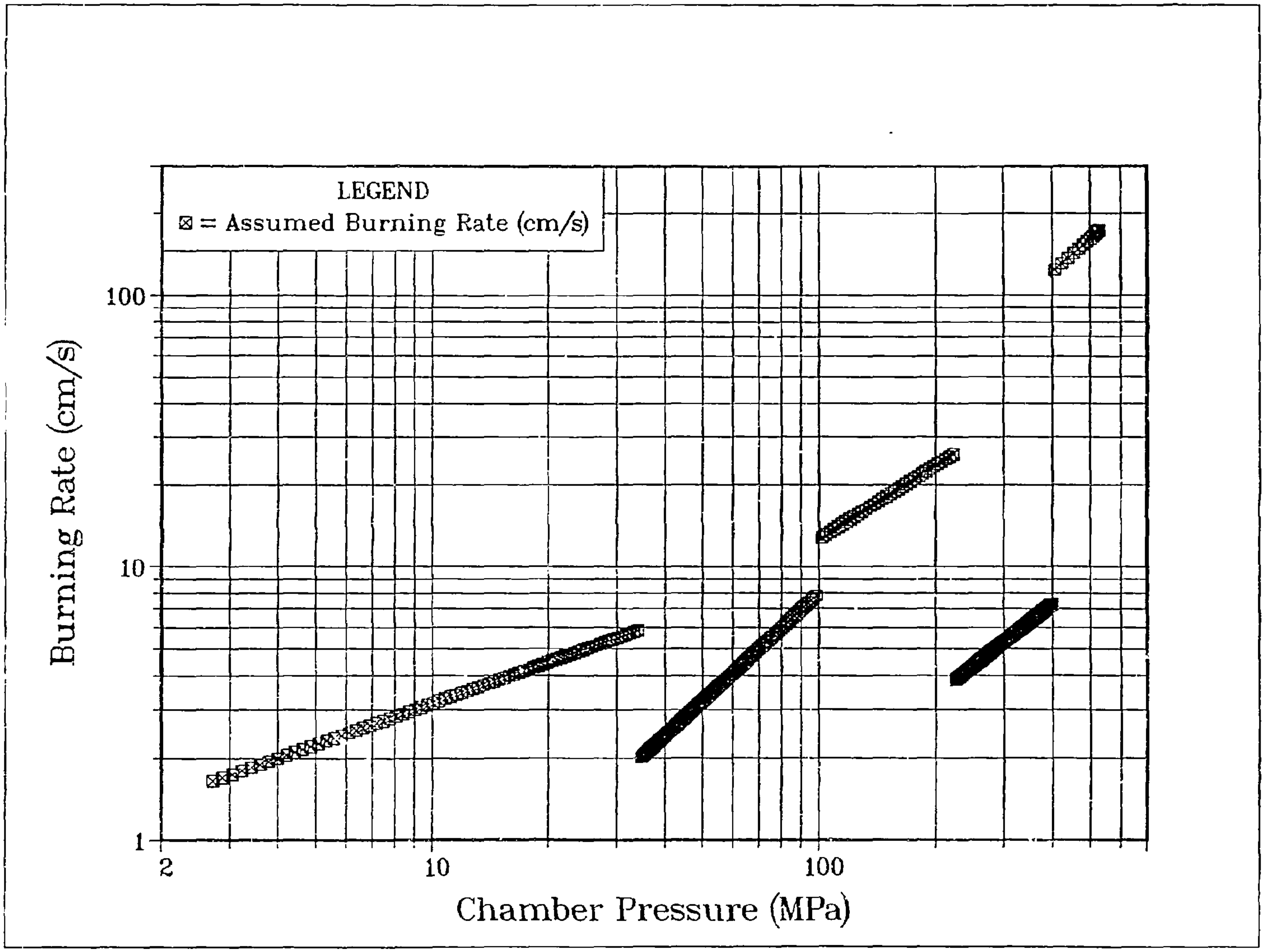

Figure 49. Assumed burn rates for five-layer sphere with varying properties in each layer, test case 19.

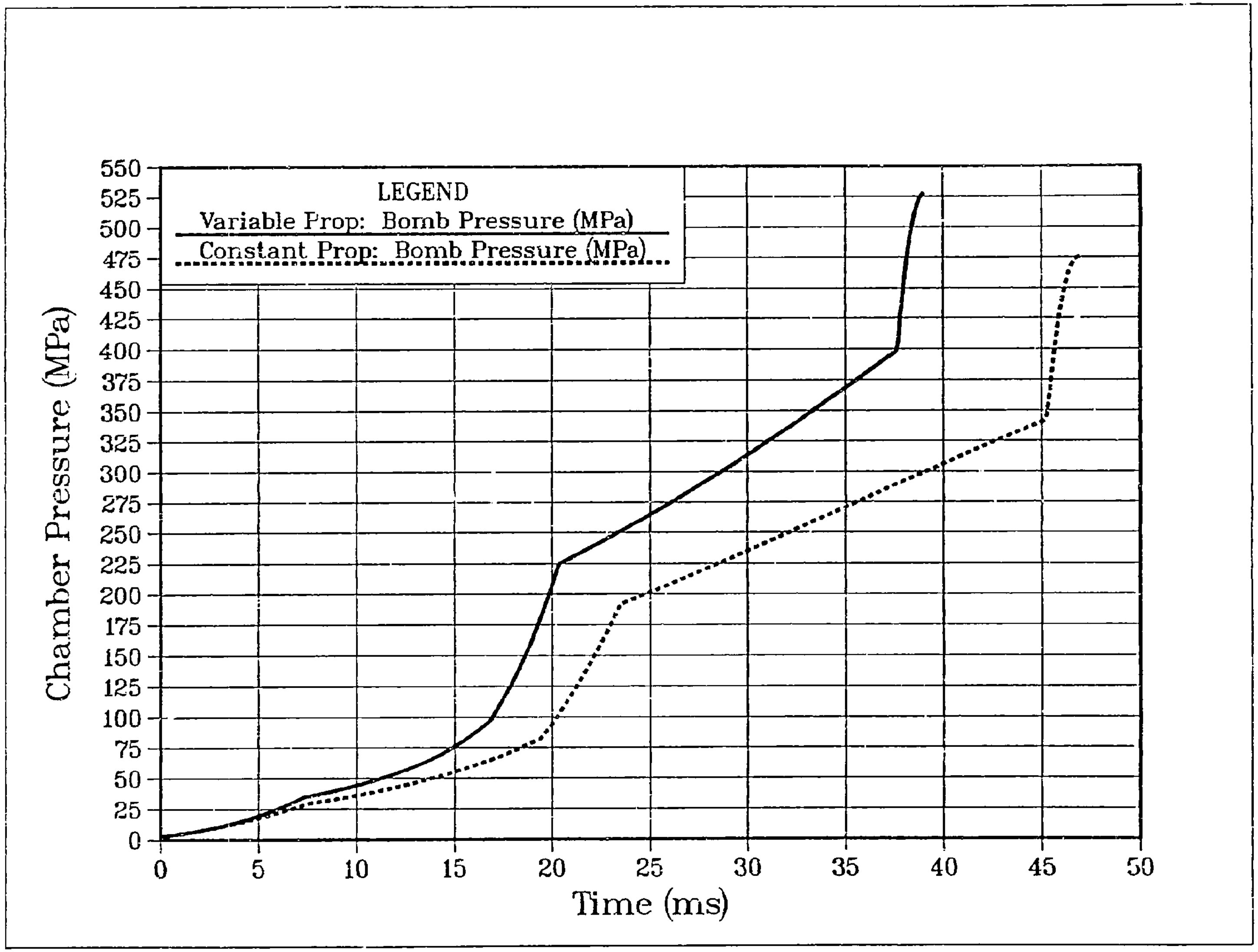

Figure 50. Pressure history generated by BRLCB for five-layer sphere with varying properties in each layer, test case 19.

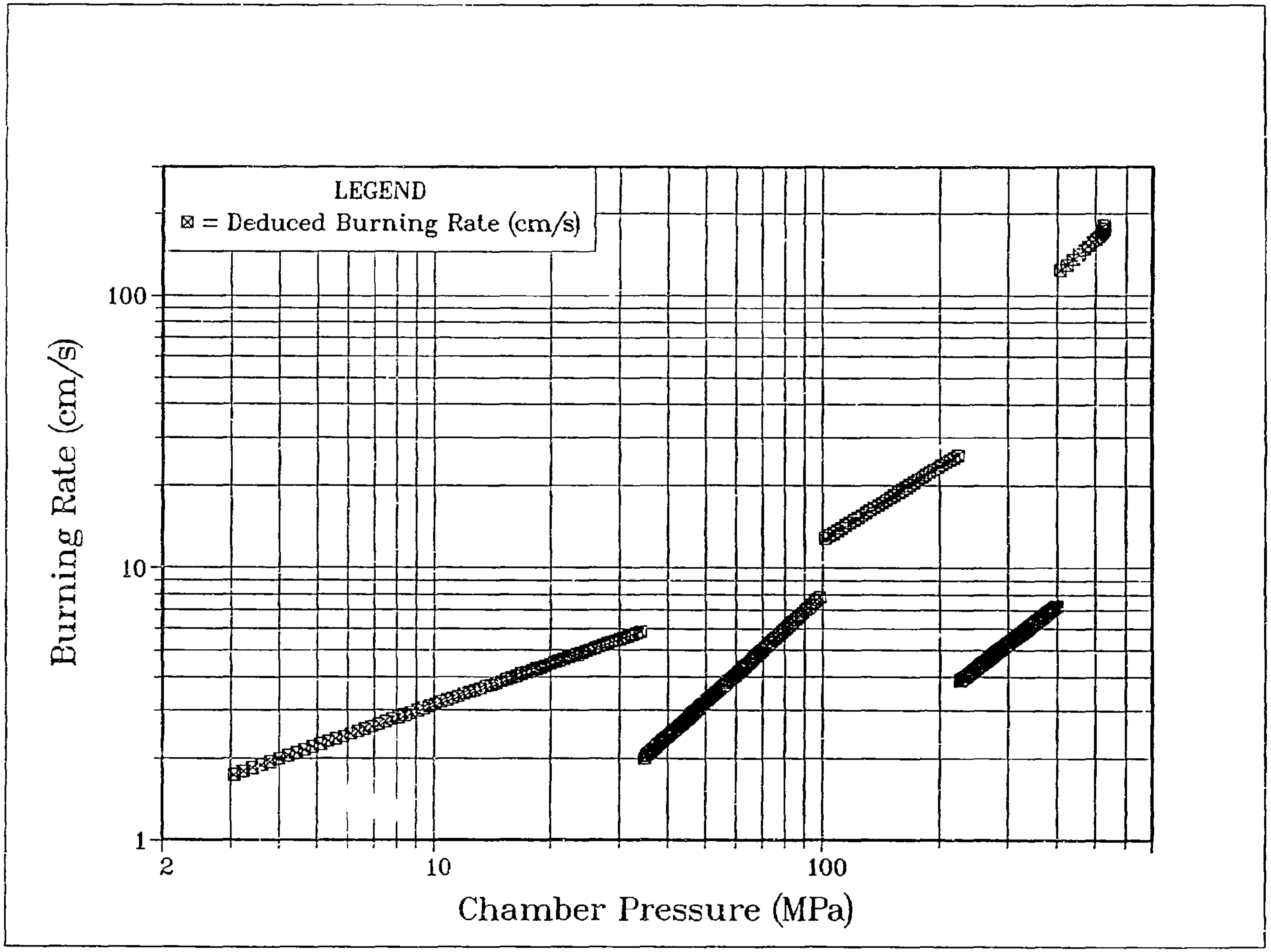

Figure 51. Deduced burning rates for five-layer sphere with varying properties in each layer, test case 19.

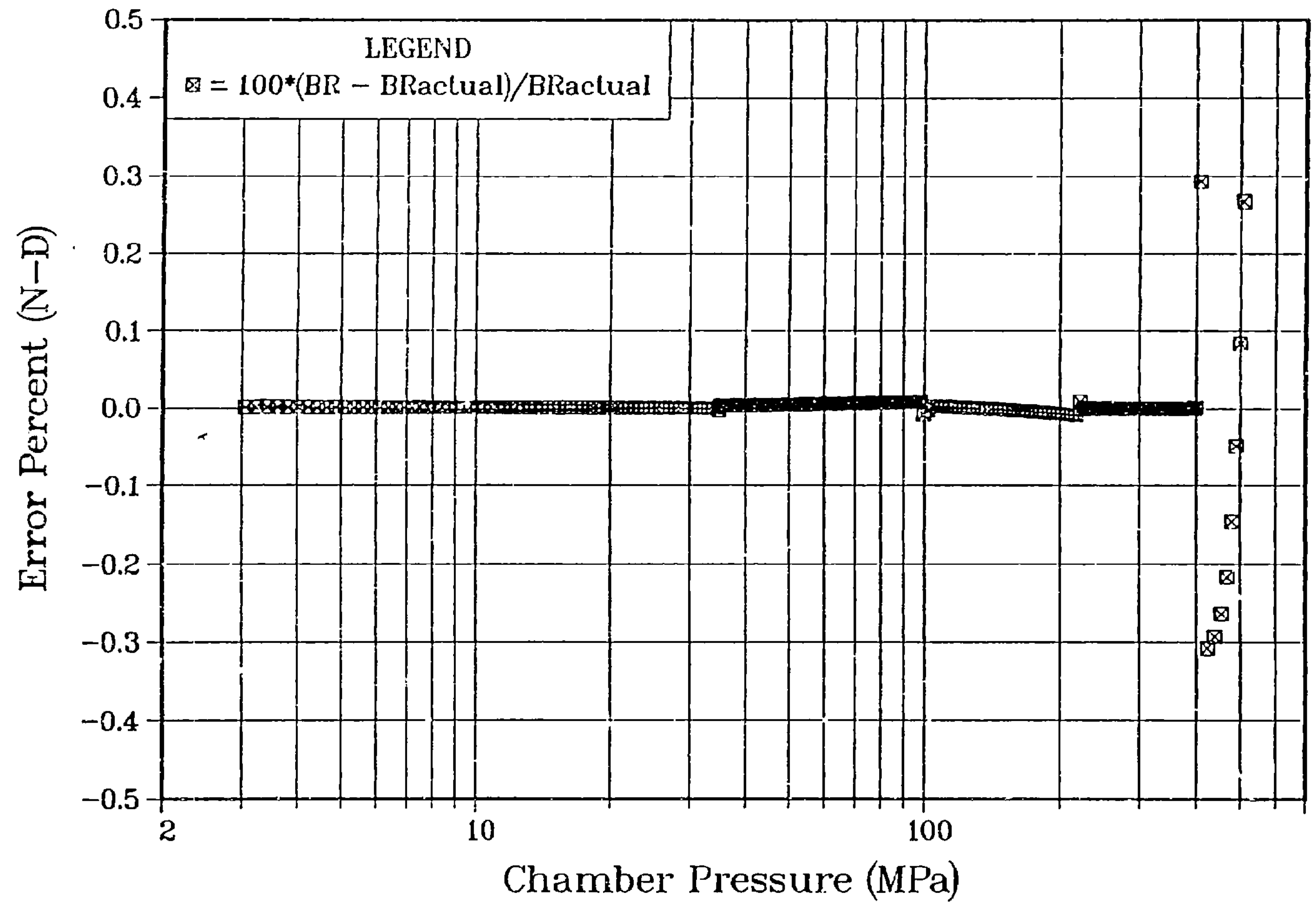

Figure 52. Percent error between BRLCB deduced burn rate and assumed burning rate, five-layer sphere with varying properties in each layer, test case 19.

5. COMPARISON WITH OTHER CLOSED-CHAMBER DATA REDUCTION PROGRAMS

In this section, burn rate reduction results from BRLCB will be discussed in comparison to results from other closed-chamber data reduction codes. The objective is not validation of the mathematical model and computer implementation, but rather to provide the user with a reference point for use when comparing or utilizing results from different reduction programs. In addition to BRLCB, three other data reduction programs have been or are still being employed by the Weapons Technology Directorate, ARL, to reduce closed-chamber data. These programs are CBRED2 (Juhasz and Price 1977); MINICB (Oberle, Juhasz, and Griffie 1987); and SIMPCB (Robbins and Horst 1976). In a comparison of the results produced by SIMPCB and BRLCB for JA2 stick propellant, Robbins (1991) found virtually no difference in the computed burn rate. Thus, comparison with SIMPCB will not be included in this report. In an earlier report (Oberle, Juhasz, and Griffie 1987), it was shown that CBRED2 and MINICB calculate burn rate equal to about 1%. Since CBRED2 is no longer available at the Weapons Technology Directorate, ARL, results from BRLCB will be compared to MINICB with the relation to CBRED2 inferred from the earlier comparison of CBRED2 and MINICB.

For the comparison, a 19-perforation grain was selected since this was the same grain geometry used in the comparison of MINICB and CBRED2. Details of the closed-chamber experiment are provided in Table 43.

Table 43. Closed Chamber Parameters

Igniter: 1.5-g black powder Propellant: 72.2715 g			
Geometry: 10-perforation		Thermochemistry	
Length (cm)	0.722884	Impetus (J/g)	1,069.0
Diameter (cm)	0.865886	Flame temperature (K)	2,671.0
Perforation diameter (cm)	0.035560	Density (g/cm^3)	1.636
Inner, outer, and middle web (cm)	0.114681	Molecular weight (–)	20.782
		Covolume (cm^3/g)	1.165
		Gamma (–)	1.2688
Bomb: 211 cm^3			

A comparison of the computed burn rate is provided in Figures 53 and 54. Figure 53 provides the complete, unfiltered, nondecimated output from BRLCB and the decimated (data points deleted) output from MINICB (MINICB automatically decimates the output to reduce the data to be processed). Figure 54 is filtered (low pass filter) BRLCB burn rate data vs. the MINICB results. A comparison of the burn rate in the figures indicates very little difference in the computed burn rate except below 10 MPa and above approximately 300 MPa. The differences above 300 MPa can be attributed to the difference in the form function used to describe the grain geometry after "silvering." BRLCB explicitly accounts for "silvering" whereas MINICB does not. This results in the computed burn rate for BRLCB remaining near linear in the 300–400 MPa range (Figure 54). To quantify the results, Table 44 compares the burn rate results for selected pressure.

As illustrated in Figure 53 and 54 and Table 44, BRLCB and MINICB produce burn rate results to within 1% (100–350 MPa) and 3% at 50 MPa. Considering that differences in the computational schemes and grain geometry form functions, the authors consider the results to be equivalent. Thus, BRLCB, at least for the limited number of cases investigated, produces equivalent results when compared to other closed-chamber data reduction programs used at the Weapons Technology Directorate, ARL.

Table 44. Comparison of Burn Rate BRLCB vs. MINICB

Pressure (MPa)	Burn Rate - BRLCB (cm/s)	Burn Rate - MINICB (cm/s)	% Difference (–)
50	3.060	3.152	+3.00
100	5.335	5.390	-1.03
150	7.168	7.165	-0.04
200	9.941	10.000	0.60
250	13.442	13.540	0.73
300	17.325	17.280	-0.26
350	20.300	20.220	-0.39
400	21.217	20.900	-1.50

6. CONCLUSIONS

BRLCB is a closed-chamber data analysis program designed to accommodate homogeneous, layered, and deterred propellants. The program offers five modes of operation: 1) burn rate analysis, 2) synthetic pressure-time history generation, 3) surface area analysis, 4) interrupted burner analysis and 5) ETC burn rate reduction. The incorporation of continuously varying thermochemical properties allows all propellant geometries to be treated as layered or deterred. Comparisons with other closed-chamber data analysis programs indicates essentially identical results.

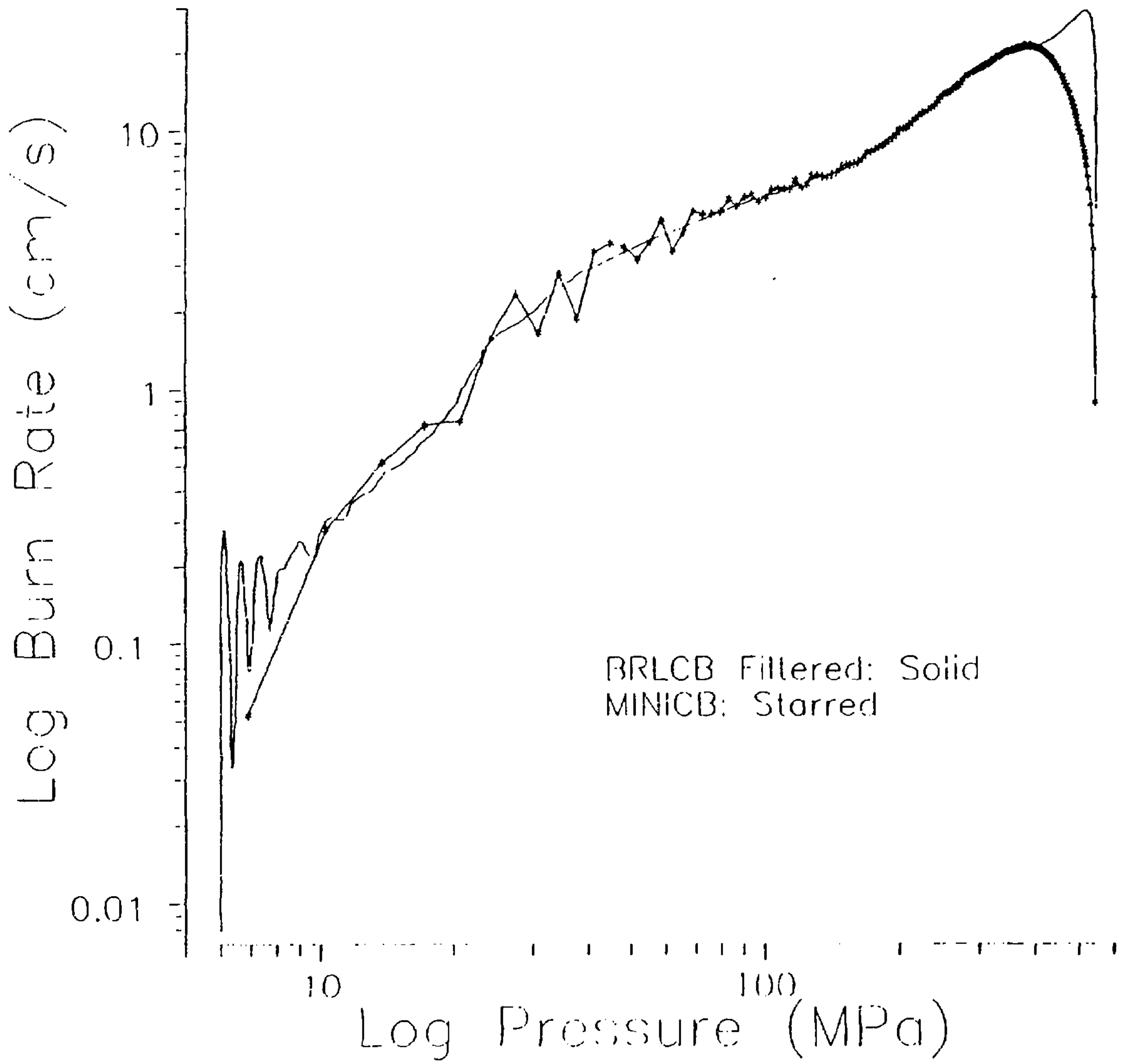

Figure 53. Comparison of burn rate results; BRLCB vs. MINICB.

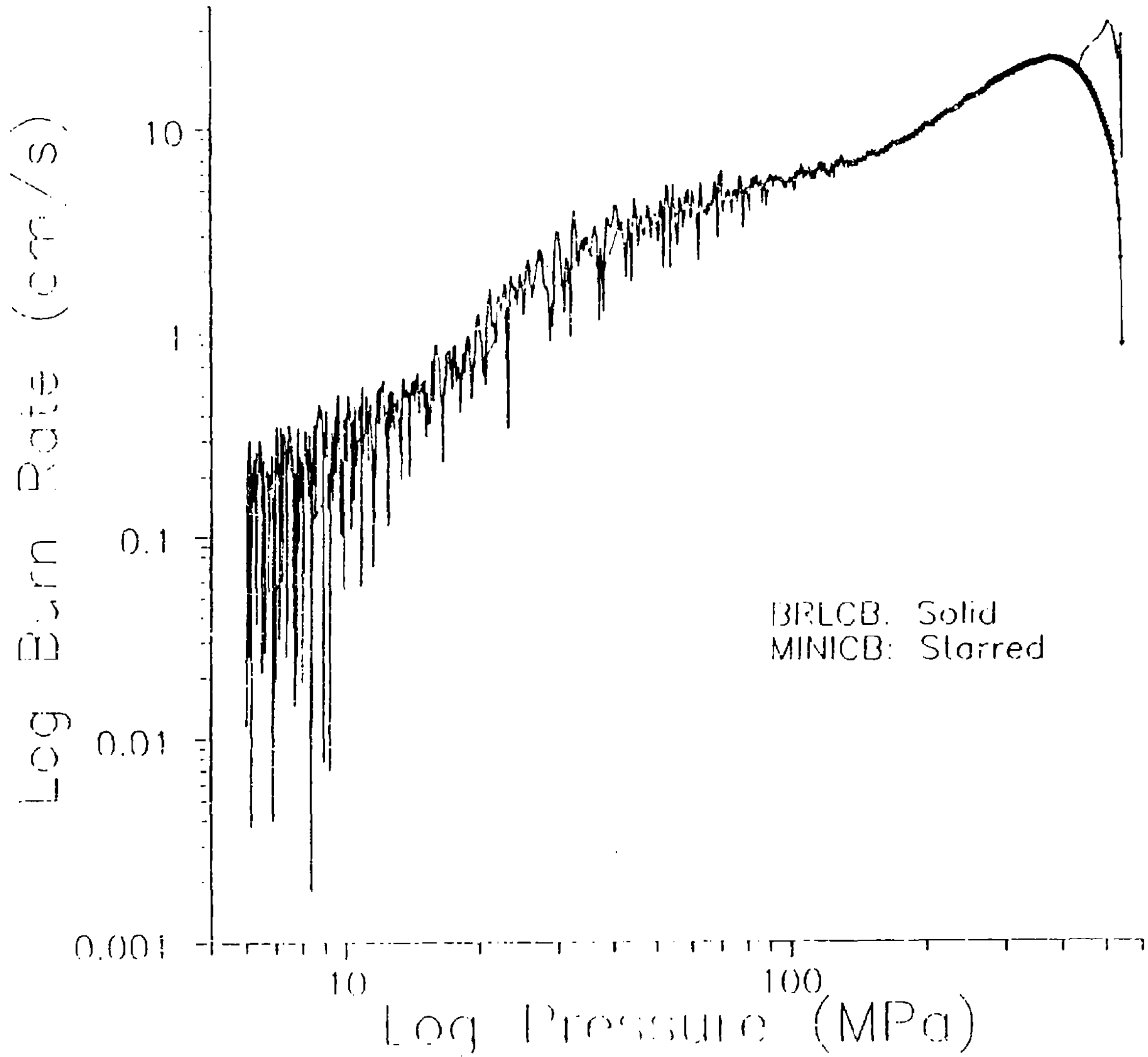

Figure 54. Comparison of burn rate results; filtered BRLCB vs. MINICB.

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7. REFERENCES

Anderson, R. A., and K. D. Fickie. "IBHVG2 - A User's Guide." BRL-TR-2829, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1987.

Doman, J. K. "Closed Bomb Data Analysis and Reporting." ARPAD-SP-88001, Picatinny Arsenal, NJ, July 1988.

Earnhart, J., and N. Winsor. "Electrothermal-Chemical Extension to IBHVG2 With a New User's Tutoria." GTD 92-1, GT-Devices, Inc., Alexandria, VA, February 1992.

Freedman, E. "BLAKE - A Thermodynamics Code Based on TIGER: User's Guide and Manual." BRL-TR-02411, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1982.

Oberle III, W. F., A. A. Juhasz, and T. Griffie. "A Simplified Computer Code for reduction to Burning Rate of Closed Bomb Pressure-Time Data (MINICB)." BRL-TR-2841, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1987.

Oberle III, W. F., and D. E. Kooker. "BRLCB: A Closed Chamber Data Analysis Program With Provisions for Deterred and Layered Propellants." Proceedings of the 26th JANNAF Combustion Meeting, Jet Propulsion Laboratory, Pasadena, CA, 1989.

Price, C., and A. Juhasz. "A Versatile User-Orientated Closed Bomb Data Reduction Program (CBRED)." BRL-R-2018, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1977.

Robbins, F. W. Private communication. U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1991.

Robbins, F. W., and A. W. Horst. "Numerical Simulation of closed Bomb Performance Based on BLAKE Code Thermodynamics Data." IHMR-76-259, Naval Ordnance Station, Indian Head, MD, 29 November 1976.

Robbins, F. W., and F. R. Lynn. "Analytic Solutions to the Closed Bomb." BRL-TR-2892, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, March 1988.

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APPENDIX A:

REQUIRED INFORMATION FOR RUNNING BRLCB

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Option 1: Create Master Information File

A. General - name of master information file if current file being created from previous file

B. Identification information

1. Project name
2. Person requesting work
3. Master information file name (.MAS extension suggested)

C. Propellant information

1. Propellant type
2. Propellant lot
3. Propellant source
4. Number of layers in grain
5. Constant or varying grain properties
6. Flame temperature (K) for each layer
7. Impetus (J/g) for each layer
8. Molecular weight (–) for each layer
9. Covolume (cc/g) for each layer
10. Ratio of specific heats (–) for each layer
11. Propellant density (g/cc) for each layer
12. Propellant grain geometry
13. Grain diameter (cm)
14. Grain length (cm) if needed
15. Perf diameter (cm) if needed
16. Inner web (cm) if needed
17. Middle web (cm) if needed
18. Outer web (cm) if needed

D. Igniter information

1. Igniter name
2. Igniter lot
3. Ingiter source
4. Igniter impetus (J/g)
5. Igniter flame temperature (K)
6. Igniter density (g/cc)
7. Igniter molecular weight (–)
8. Igniter covolume (cc/g)
9. Igniter ratio of specific heats (–)

Option 2: Update gage information

1. Gage ID
2. Gage calibration date
3. Gage calibration coefficients (second order fit to produce MPa)

Option 3: Prepare pressure/time data

1. Format of pressure/time data (see Table 13)
2. Name of pressure/time data file
3. Output file name for pressure/time data (all files for the reduction will use this file name)
4. Time step for data in milliseconds
5. Using VuPoint/BRL procedure - calibration voltage of charge amplifier

Option 4: Repare firing information file

1. Name of master file to be utilized in creating the firing information file
2. Type of computation (see table 17)
3. Name of pressure/time file created in Option 3 to be used in the reduction
4. Closed chamber volume (cc)
5. Initial temperature of closed chamber (K)
6. Propellant mass (g)
7. Ignition mass (g)
8. Initial propellant temperature (K)
9. Initial igniter temperature (K)
10. Ranges for burn rate low computations
11. For ETC option - name of electrical energy file

Option 5: Smooth pressure/time data

1. Type printer
2. File name (same name as firing information file)
3. Bridge length option
4. Number of wildpoint removal passes
5. Wildpoint tolerance
6. Number of smoothing passes
7. Bridge length (fixed bridge length option only)
8. Pressure in MPa associated with grain slivering (if slivering option selected)
9. Make pressure strictly monotonic? (yes/no)
10. Vivacity information required? (yes/no)

Option 6: Perform data analysis

1. Set closed chamber air mass to 0.0? (yes/no)
2. Change heat loss fraction? (yes/no) If yes, new value for heat loss fraction.

Option 7: Prepare output

1. File name
2. Date of closed chamber firing
3. Comments on firing
4. Comments on reduction
5. Type output (hard copy, file or both)
6. Printer port (LPT1, etc.)
7. Number of lines per printed page

8. Skip factor for printing tabular data
9. FFT on burn rate? (yes/no)
10. Printer type
11. Pressure ranges for bP^n burn rate laws
12. Summary output sheet? (yes/no)

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APPENDIX B:

FILE STRUCTURE: .MAS AND .INF FILES

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Lines 1–6: Array A2(1) through A2(6)
Format A80
Comments on the firing and reduction

Lines 7–26: Array A1(1) through A1(20)
Format A20

Line 7: A1(1)	Project name
Line 8: A1(2)	Person requesting work
Line 9: A1(3)	Master file name
Line 10: A1(4)	INF file name
Line 11: A1(5)	.PVT file name
Line 12: A1(6)	Propellant type
Line 13: A1(7)	Propellant lot
Line 14: A1(8)	Propellant source
Line 15: A1(9)	Name of grain geometry
Line 16: A1(10)	Output file name
Line 17: A1(11)	Igniter name
Line 18: A1(12)	Igniter lot
Line 19: A1(13)	Igniter source
Line 20: A1(14)	.PDT file name
Line 21: A1(15)	Gage identification number
Line 22: A1(16)	Bomb type (closed or interrupted)
Line 23: A1(17)	Graphics file name
Line 24: A1(18)	Computed burn rate data
Line 25: A1(19)	Electrical energy file name
Line 26: A1(20)	Date of firing

Lines 27 through 126: Array A3(1)–A3(100)

Line 27:A3(1)	Maximum grain depth for burning
Line 28:A3(2)	Calculation mode: (1=burn rate; 2=pressure generation; 3=surface area; 4=interrupted burner; 5=ETC burn rate)
Line 29: A3(3)	Mass (grams) of a single grain
Line 30: A3(4)	Number of layers per grain
Line 31: A3(5)	Number of burn rate pairs (negative number: bP^n laws; positive number: tabular pressure-burn rate information)
Line 32: A3(6)	Not used
Line 33: A3(7)	Grain length (cm)
Line 34: A3(8)	Grain outer diameter (cm)
Line 35: A3(9)	Grain perf diameter (cm)
Line 36: A3(10)	Grain inner web (cm)
Line 37: A3(11)	Grain middle web (cm)
Line 38: A3(12)	Grain outer web (cm)
Line 39: A3(13)	Igniter impetus (J/g)
Line 40: A3(14)	Igniter flame temperature (K)
Line 41: A3(15)	Igniter density (g/cc)
Line 42: A3(16)	Igniter molecular weight
Line 43: A3(17)	Igniter covolume (cc/g)

Line 44: A3(18) Igniter ratio of specific heats
Line 45: A3(19) Gage input voltage (volts)
Line 46: A3(20) Constant in gage fit
Line 47: A3(21) Linear term in gage fit
Line 48: A3(22) Quadratic in gage fit
Line 49: A3(23) Bomb volume (cc)
Line 50: A3(24) Initial bomb temperature (K)
Line 51: A3(25) Total propellant mass (grams)
Line 52: A3(26) Igniter mass (grams)
Line 53: A3(27) Initial propellant temperature (K)
Line 54: A3(28) Initial igniter temperature (K)
Line 55: A3(29) Pressure due to igniter (MPa)
Line 56: A3(30) Total electrical energy (MJ)
Line 57: A3(31) Flag for grain type (0=variable layers; 1=homogeneous, one layer; 2=homogeneous layers, several layers)
Line 58: A3(32) through Line 67: A3(41) Not used
Line 68: A3(42) Time step in milliseconds
Line 69: A3(43) Observed maximum pressure
Line 70: A3(44) Theoretical maximum pressure
Line 71: A3(45) Grain geometry number
Line 72: A3(46) Number of propellant grains
Line 73: A3(47) Not used
Line 74: A3(48) Not used
Line 75: A3(49) Not used
Line 76: A3(50) through Line 125: A3(99) contain the burn rate law information; absolute value of A3(5) determines the number of pairs. If A3(5) is negative, then bP^n burn rate laws are used. These laws are stored in the following manner.

A3(50) - first law coefficient, A3(51) - corresponding exponent,
A3(52) - second law coefficient, A3(53) - corresponding exponents, etc.

If A3(5) is positive, the tabular pressure-burn rate information is stored in the following manner.

A3(50)–A3(79): Pressures in MPA
A3(80)–A3(99): Corresponding burn rate (cm/s)

Line 126: A3(100) Number of computational steps performed

The remaining 825 lines of the file contain properties of a single grain of the propellant and storage locations for the computation. These 825 lines are thought of as a three-dimensional array, PX(11,15,5). The information is written in the following manner.

```
DO 10 I=1,11
DO 20 J=1,15
DO 30 K=1,5
WRITE(-,*)PX(I,J,K)
```

```
30      CONTINUE
20      CONTINUE
10      CONTINUE
```

The structure of the array PX is as follows:

PX(I,J,K):
  I=property
  1 = Depths into grain (0.0 is depth of outer layer)
  2 = Impetus (J/g)
  3 = Flame temperature (K)
  4 = Density (g/cc)
  5 = Molecular weight (–)
  6 = Covolume (cc/g)
  7 = Ratio of specific heats, gamma
  8 = Volume if K is 3, 4, or 5
  Value of 1 for K a i or 2
  9 = Universal gas constant (cal/g-K)
  10 = Ratio of specific heat, constant volume (cal/g-K)
  11 = Specific energy (cal/g)

  J = layer

  K = determines specific content of array cell
  1 = value at beginning of layer
  2 = value at end of layer
  3 = value of integration over entire layer

  Integral = Integral (Property * Density * dx)

  4 = value of last converged integral
  5 = value of last computed integral

Exceptions:

PX(1,-,1):	beginning depth of layer
PX(1,-,2):	depth or length of layer, not the depth at the end of the layer
PX(1,-,3):	Not used
PX(1,-,4):	depth for last converged integral
PX(1,-,5):	depth for last computed integral

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APPENDIX C:

SAMPLE OUTPUT

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BURNING RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

Project:	Test of 7-perf	Requested by:	oberle
Inf File:	a:perf7.inf	Created From .MAS File:	a:perf7.mas
P/T File:	a:perf7.pvt	Calculation Output File:	a:perf7.out
Smoothed:	a:perf7.pdt	Graphics File:	a:perf7.dat
Fired on:	2/23/92		

IGNITER INFORMATION

The igniter used is: Dummy JA2 Lot: Dummy
The source for the igniter is: William Oberle

IGNITER THERMOCHEMICAL PROPERTIES

Impetus (J/g):	1,140.0	Molecular Weight:	24.86900
Flame Temperature (K):	3,410.0	Covolume (cc/g):	.99600
Density (g/cc):	1.58000	Gamma:	1.22500

PROPELLANT INFORMATION

The propellant used is: JA2 Lot: Dummy
The source for the propellant is: oberle

Propellant Thermochemical Properties: Following Sheets of Output

PROPELLANT GRAIN GEOMETRY

Grain Type: 7-Per. Cyl.

Length (cm):	2.000000
Outer Diam. (cm):	1.300000
Perf Diam. (cm):	.100000
Inner Web (cm):	.200000
Outer Web (cm):	.300000

Bomb Information		Gage Information	
Bomb Type:	Closed Chamber	Gage ID:	None
Bomb Vol (cc):	300.0	Input Voltage:	.0000

Constants for Fit: A+Bx+C^2
A: .00000E+00
B: .00000E+00
C: .00000E+00

Temperature and Charge Mass Information

Propellant Mass (g):	90.0000	Igniter Mass (g):	1.0000
Initial Temp. Prop. (K):	294.	Igniter Temp. (K):	294.
Initial Bomb Temp. (K):	294.		
Number of Propellant grains:	22.38		

```
Total # Layers =              1
Chamber Volume (cm3) =   300.000
Heat-Loss-Fraction (n-d) =  .000
Time Step (ms) =              .50000000E-01        Max Time steps =  1,200
Convergence Criterion =       .10000000E-04
Computation type (1=BURN-RATE, 2=PTGEN, 3=SURF AREA, 4=INTERR BOMB, 5=ETC)
1
********************************************************************************
    Beginning(1) of Layer              End(2) of Layer
********************************************************************************
    Propellant Mass in grams
********************************************************************************
    1                  90.00002
    Igniter            1.00000
    Air                .00000
********************************************************************************
    Propellant Density in g/cc
********************************************************************************
    1                  1.58000          1.58000
    Igniter            1.58000
********************************************************************************
    Propellant Impetus in J/g
********************************************************************************
    1                  1140.00000       1140.00000
    Igniter            1140.00000
********************************************************************************
    Propellant Flame Temperature in deg K
********************************************************************************
    1                  3410.00000       3410.00000
    Igniter            3410.00000
********************************************************************************
    Propellant Molecular Weight in g/g-mole
********************************************************************************
    1                  24.86907         24.86907
    Igniter            24.86900
    Air                28.90000
********************************************************************************
    Propellant Gas Constant in cal/g-deg K
********************************************************************************
    1                  .07991           .07991
    Igniter            .07991
    Air                .06876
********************************************************************************
    Gamma (Ratio of Specific Heats)
********************************************************************************
    1                  1.22500          1.22500
    Igniter            1.22500
    Air                1.40000
********************************************************************************
```

Specific Heat (Cv) in cal/g-deg k

1	.35513	.35513
Igniter	.35514	
Air	.17190	

Covolume in cm3/g

1	.99600	.99600
Igniter	.99600	
Air	.98000	

******* Maximum Chamber *******
Theoretical Maximum Chamber Pressure (MPa) = .49552060E+03
Theoretical Maximum Chamber Temperature (deg K) = .34100000E+04
*** Assuming a Heat-Loss-Fraction = .000
Maximum Total Heat Loss From Chamber (cal) = -.43689020E-02
Maximum Chamber Pressure (MPa) w/Heat Loss = .49552060E+03
Maximum Chamber Temperature (deg K) w/Heat Loss = .34100000E+04
** Results: Deduced Burning Rates Based on a Given Chamber Pressure vs. Time **
*** N *** LAYER *** TIME(ms) *** PCH(MPa) *** TPMR(gm) *** RBR(cm/s) *** ASUR(cm2) *** TCH(degK) *** DEPTH(cm) ***

N= 1 LAYER= 1	.00000000E+00	.47101240E+01	.90000020E+02	.00000000E+00	.33825600E+03	.34099980E+04	.00000000E+00

*** DEDUCED BURNING RATES ***

N= 3 LAYER= 1	.99999990E-01	.48773000E+01	.89964920E+02	.64473380E+00	.33825600E+03	.34099980E+04	.00000000E+00
N= 4 LAYER= 1	.15000000E+00	.49631000E+01	.89947350E+02	.69358250E+00	.33825600E+03	.34099980E+04	.00000000E+00
N= 5 LAYER= 1	.20000000E+00	.50502000E+01	.89927850E+02	.70646360E+00	.33825600E+03	.34099980E+04	.00000000E+00
N= 6 LAYER= 1	.25000000E+00	.51387000E+01	.89909590E+02	.70639910E+00	.33844710E+03	.34100150E+04	.16992880E-03
N= 7 LAYER= 1	.30000000E+00	.52286000E+01	.89890080E+02	.71901880E+00	.33848830E+03	.34100150E+04	.20657420E-03
N= 8 LAYER= 1	.35000000E+00	.53200000E+01	.89871140E+02	.71993710E+00	.33852810E+03	.34100150E+04	.24199160E-03
N= 9 LAYER= 1	.40000000E+00	.54129000E+01	.89851570E+02	.75427930E+00	.33856930E+03	.34100150E+04	.27862350E-03
N= 10 LAYER= 1	.45000000E+00	.55072000E+01	.89830800E+02	.76655350E+00	.33861040E+03	.34100150E+04	.31525120E-03
N= 11 LAYER= 1	.50000010E+00	.56030000E+01	.89810560E+02	.75743130E+00	.33865440E+03	.34100140E+04	.35431020E-03
N= 12 LAYER= 1	.55000000E+00	.57004000E+01	.89790260E+02	.75967260E+00	.33869820E+03	.34100140E+04	.39336140E-03
N= 13 LAYER= 1	.60000000E+00	.57993000E+01	.89769910E+02	.79265960E+00	.33873790E+03	.34100140E+04	.42874760E-03
N= 14 LAYER= 1	.65000000E+00	.58998000E+01	.89747840E+02	.80557930E+00	.33878450E+03	.34100140E+04	.47022370E-03
N= 15 LAYER= 1	.70000000E+00	.60019000E+01	.89726780E+02	.80763940E+00	.33883110E+03	.34100130E+04	.51168840E-03
N= 16 LAYER= 1	.75000000E+00	.61056000E+01	.89704610E+02	.83959590E+00	.33887490E+03	.34100130E+04	.55071110E-03
N= 17 LAYER= 1	.80000000E+00	.62110000E+01	.89681830E+02	.85199230E+00	.33892550E+03	.34100130E+04	.59581610E-03
N= 18 LAYER= 1	.85000000E+00	.63180000E+01	.89658980E+02	.85487690E+00	.33897340E+03	.34100120E+04	.63847590E-03
N= 19 LAYER= 1	.89999990E+00	.64268000E+01	.89636050E+02	.86727420E+00	.33902120E+03	.34100120E+04	.68112630E-03
N= 20 LAYER= 1	.95000000E+00	.65372000E+01	.89612530E+02	.88016470E+00	.33907040E+03	.34100120E+04	.72498540E-03
N= 21 LAYER= 1	.10000000E+01	.66494000E+01	.89588890E+02	.87537030E+00	.33911820E+03	.34100120E+04	.76761930E-03
N= 22 LAYER= 1	.10500000E+01	.67634000E+01	.89565620E+02	.89726980E+00	.33916600E+03	.34100120E+04	.81024140E-03
N= 23 LAYER= 1	.11000000E+01	.68792000E+01	.89540810E+02	.93632580E+00	.33922060E+03	.34100120E+04	.85893860E-03
N= 24 LAYER= 1	.11500000E+01	.69968000E+01	.89515430E+02	.94868800E+00	.33927380E+03	.34100120E+04	.90640930E-03
N= 25 LAYER= 1	.12000000E+01	.71162000E+01	.89489950E+02	.94487150E+00	.33932700E+03	.34100110E+04	.95386860E-03
N= 26 LAYER= 1	.12500000E+01	.72375000E+01	.89464780E+02	.95823690E+00	.33937740E+03	.34100110E+04	.99888560E-03
N= 27 LAYER= 1	.13000000E+01	.73608000E+01	.89438580E+02	.97992010E+00	.33943190E+03	.34100110E+04	.10475380E-02
N= 28 LAYER= 1	.13500000E+01	.74859000E+01	.89412220E+02	.10007670E+01	.33948630E+03	.34100110E+04	.10961790E-02
N= 29 LAYER= 1	.14000000E+01	.76130000E+01	.89384900E+02	.10217550E+01	.33954620E+03	.34100110E+04	.11496670E-02
N= 30 LAYER= 1	.14500000E+01	.77420990E+01	.89357410E+02	.10274190E+01	.33960200E+03	.34100110E+04	.11995000E-02
N= 31 LAYER= 1	.15000000E+01	.78732000E+01	.89329770E+02	.10412400E+01	.33965910E+03	.34100100E+04	.12505330E-02
N= 32 LAYER= 1	.15500000E+01	.80064000E+01	.89301530E+02	.10480500E+01	.33972020E+03	.34100100E+04	.13051930E-02
N= 33 LAYER= 1	.16000000E+01	.81417000E+01	.89273510E+02	.10618590E+01	.33977870E+03	.34100100E+04	.13574120E-02
N= 34 LAYER= 1	.16500000E+01	.82790000E+01	.89244520E+02	.10906490E+01	.33983700E+03	.34100100E+04	.14096210E-02
N= 35 LAYER= 1	.17000000E+01	.84185000E+01	.89214950E+02	.11050930E+01	.33990080E+03	.34100100E+04	.14666640E-02
N= 36 LAYER= 1	.17500000E+01	.85602000E+01	.89185170E+02	.11258700E+01	.33996180E+03	.34100100E+04	.15212670E-02

N= 37	LAYER= 1	.18000000E+01	.87040000E+01	.89154470E+02	.11471220E+01	.34002690E+03	.34100100E+04	.15794930E-02
N= 38	LAYER= 1	.18500000E+01	.88501000E+01	.89123550E+02	.11552340E+01	.34008780E+03	.34100100E+04	.16340670E-02
N= 39	LAYER= 1	.19000000E+01	.89985000E+01	.89092400E+02	.11829540E+01	.34015550E+03	.34100090E+04	.16946810E-02
N= 40	LAYER= 1	.19500000E+01	.91491000E+01	.89059970E+02	.11915410E+01	.34022050E+03	.34100090E+04	.17528580E-02
N= 41	LAYER= 1	.20000000E+01	.93021000E+01	.89028340E+02	.12001190E+01	.34028810E+03	.34100090E+04	.18134350E-02
N= 42	LAYER= 1	.20500000E+01	.94575000E+01	.88995450E+02	.12407880E+01	.34035430E+03	.34100090E+04	.18727870E-02
N= 43	LAYER= 1	.21000000E+01	.96153000E+01	.88961620E+02	.12498360E+01	.34042450E+03	.34100090E+04	.19357520E-02
N= 44	LAYER= 1	.21500000E+01	.97754000E+01	.88928220E+02	.12650290E+01	.34049610E+03	.34100090E+04	.19999020E-02
N= 45	LAYER= 1	.22000000E+01	.99381000E+01	.88893560E+02	.12867000E+01	.34056760E+03	.34100080E+04	.20640360E-02
N= 46	LAYER= 1	.22500000E+01	.10103000E+02	.88858990E+02	.13090200E+01	.34063910E+03	.34100080E+04	.21281470E-02
N= 47	LAYER= 1	.23000000E+01	.10271000E+02	.88823110E+02	.13253460E+01	.34071180E+03	.34100080E+04	.21934490E-02
N= 48	LAYER= 1	.23500000E+01	.10441000E+02	.88787640E+02	.13466390E+01	.34078720E+03	.34100080E+04	.22611410E-02
N= 49	LAYER= 1	.24000000E+01	.10614000E+02	.88750600E+02	.13705790E+01	.34086260E+03	.34100080E+04	.23288160E-02
N= 50	LAYER= 1	.24500000E+01	.10790000E+02	.88713820E+02	.13862100E+01	.34093920E+03	.34100080E+04	.23976710E-02
N= 51	LAYER= 1	.25000000E+01	.10968000E+02	.88675930E+02	.14077990E+01	.34101580E+03	.34100080E+04	.24665050E-02
N= 52	LAYER= 1	.25500000E+01	.11149000E+02	.88637970E+02	.14313530E+01	.34109640E+03	.34100080E+04	.25389290E-02
N= 53	LAYER= 1	.26000000E+01	.11333000E+02	.88598790E+02	.14578870E+01	.34117690E+03	.34100080E+04	.26113300E-02
N= 54	LAYER= 1	.26500000E+01	.11519000E+02	.88559380E+02	.14659970E+01	.34125740E+03	.34100080E+04	.26837050E-02
N= 55	LAYER= 1	.27000000E+01	.11709000E+02	.88519740E+02	.14845410E+01	.34134050E+03	.34100080E+04	.27584620E-02
N= 56	LAYER= 1	.27500000E+01	.11901000E+02	.88479320E+02	.15110330E+01	.34142350E+03	.34100080E+04	.28331910E-02
N= 57	LAYER= 1	.28000000E+01	.12096000E+02	.88438230E+02	.15464570E+01	.34150520E+03	.34100070E+04	.29066900E-02
N= 58	LAYER= 1	.28500000E+01	.12295000E+02	.88395870E+02	.15743840E+01	.34159340E+03	.34100070E+04	.29861790E-02
N= 59	LAYER= 1	.29000000E+01	.12496000E+02	.88353260E+02	.15812710E+01	.34168020E+03	.34100070E+04	.30644320E-02
N= 60	LAYER= 1	.29500000E+01	.12700000E+02	.88310510E+02	.16023900E+01	.34176840E+03	.34100070E+04	.31438560E-02
N= 61	LAYER= 1	.30000000E+01	.12908000E+02	.88266730E+02	.16347360E+01	.34186040E+03	.34100070E+04	.32268520E-02
N= 62	LAYER= 1	.30500000E+01	.13118000E+02	.88222210E+02	.16581330E+01	.34194970E+03	.34100070E+04	.33074140E-02
N= 63	LAYER= 1	.31000000E+01	.13332000E+02	.88177150E+02	.16752100E+01	.34204430E+03	.34100070E+04	.33927440E-02
N= 64	LAYER= 1	.31500000E+01	.13549000E+02	.88131680E+02	.17027250E+01	.34213480E+03	.34100060E+04	.34744390E-02
N= 65	LAYER= 1	.32000000E+01	.13769000E+02	.88085110E+02	.17326690E+01	.34223050E+03	.34100060E+04	.35608990E-02
N= 66	LAYER= 1	.32500000E+01	.13993000E+02	.88037990E+02	.17582920E+01	.34232750E+03	.34100060E+04	.36485190E-02
N= 67	LAYER= 1	.33000000E+01	.14220000E+02	.87990000E+02	.17776250E+01	.34242580E+03	.34100060E+04	.37372990E-02
N= 68	LAYER= 1	.33500000E+01	.14450000E+02	.87941810E+02	.18070140E+01	.34252390E+03	.34100060E+04	.38260380E-02
N= 69	LAYER= 1	.34000000E+01	.14684000E+02	.87892200E+02	.18365350E+01	.34262460E+03	.34100060E+04	.39171330E-02
N= 70	LAYER= 1	.34500000E+01	.14921000E+02	.87842390E+02	.18480340E+01	.34272790E+03	.34100060E+04	.40105820E-02
N= 71	LAYER= 1	.35000000E+01	.15161000E+02	.87792140E+02	.18839700E+01	.34282980E+03	.34100060E+04	.41027900E-02
N= 72	LAYER= 1	.35500000E+01	.15406000E+02	.87740340E+02	.19224960E+01	.34293680E+03	.34100060E+04	.41997350E-02
N= 73	LAYER= 1	.36000000E+01	.15655000E+02	.87687970E+02	.19416840E+01	.34304370E+03	.34100060E+04	.42966350E-02
N= 74	LAYER= 1	.36500000E+01	.15906000E+02	.87635100E+02	.19709260E+01	.34314930E+03	.34100060E+04	.43922940E-02
N= 75	LAYER= 1	.37000000E+01	.16162000E+02	.87581110E+02	.20024450E+01	.34325990E+03	.34100060E+04	.44926810E-02
N= 76	LAYER= 1	.37500000E+01	.16421000E+02	.87526500E+02	.20207440E+01	.34337190E+03	.34100060E+04	.45942110E-02

N=	77	LAYER= 1	.38000000E+01	.16684000E+02	.87471470E+02	.20522110E+01	.34348360E+03	.34100060E+04	.46956860E-02
N=	78	LAYER= 1	.38500000E+01	.16952000E+02	.87415120E+02	.20879240E+01	.34359800E+03	.34100060E+04	.47994920E-02
N=	79	LAYER= 1	.39000000E+01	.17222000E+02	.87358120E+02	.21191620E+01	.34371340E+03	.34100050E+04	.49044350E-02
N=	80	LAYER= 1	.39500000E+01	.17498000E+02	.87300040E+02	.21530030E+01	.34382880E+03	.34100050E+04	.50093260E-02
N=	81	LAYER= 1	.40000000E+01	.17778000E+02	.87241170E+02	.21810400E+01	.34394940E+03	.34100050E+04	.51189180E-02
N=	82	LAYER= 1	.40500000E+01	.18062000E+02	.87181510E+02	.22153170E+01	.34407100E+03	.34100050E+04	.52296370E-02
N=	83	LAYER= 1	.41000000E+01	.18351000E+02	.87120740E+02	.22465760E+01	.34419390E+03	.34100050E+04	.53414840E-02
N=	84	LAYER= 1	.41500000E+01	.18644000E+02	.87059330E+02	.22745350E+01	.34431660E+03	.34100050E+04	.54532680E-02
N=	85	LAYER= 1	.42000000E+01	.18940000E+02	.86996990E+02	.23086930E+01	.34444180E+03	.34100050E+04	.55673610E-02
N=	86	LAYER= 1	.42500000E+01	.19241000E+02	.86933690E+02	.23397060E+01	.34456810E+03	.34100050E+04	.56825740E-02
N=	87	LAYER= 1	.43000000E+01	.19546000E+02	.86869610E+02	.24117200E+01	.34469960E+03	.34100050E+04	.58024600E-02
N=	88	LAYER= 1	.43500000E+01	.19867000E+02	.86802350E+02	.24485080E+01	.34483470E+03	.34100050E+04	.59258330E-02
N=	89	LAYER= 1	.44000000E+01	.20182000E+02	.86736210E+02	.24524990E+01	.34496580E+03	.34100050E+04	.60455720E-02
N=	90	LAYER= 1	.44500000E+01	.20503000E+02	.86668670E+02	.24918780E+01	.34510190E+03	.34100050E+04	.61699720E-02
N=	91	LAYER= 1	.45000000E+01	.20828000E+02	.86600340E+02	.25113470E+01	.34524050E+03	.34100050E+04	.62966520E-02
N=	92	LAYER= 1	.45500000E+01	.21156000E+02	.86531680E+02	.25862170E+01	.34537630E+03	.34100050E+04	.64208910E-02
N=	93	LAYER= 1	.46000000E+01	.21502000E+02	.86459210E+02	.26339290E+01	.34552350E+03	.34100040E+04	.65556800E-02
N=	94	LAYER= 1	.46500000E+01	.21842000E+02	.86387890E+02	.26294100E+01	.34566530E+03	.34100050E+04	.66856510E-02
N=	95	LAYER= 1	.47000000E+01	.22187000E+02	.86315610E+02	.26715330E+01	.34580830E+03	.34100050E+04	.68167190E-02
N=	96	LAYER= 1	.47500000E+01	.22538000E+02	.86241930E+02	.27045650E+01	.34595500E+03	.34100040E+04	.69512300E-02
N=	97	LAYER= 1	.48000000E+01	.22892000E+02	.86167770E+02	.27840140E+01	.34610280E+03	.34100040E+04	.70868230E-02
N=	98	LAYER= 1	.48500000E+01	.23264000E+02	.86089680E+02	.28294950E+01	.34626060E+03	.34100040E+04	.72317420E-02
N=	99	LAYER= 1	.49000000E+01	.23631000E+02	.86012970E+02	.28251460E+01	.34641300E+03	.34100040E+04	.73718460E-02
N=	100	LAYER= 1	.49500000E+01	.24003000E+02	.85935050E+02	.29099430E+01	.34656790E+03	.34100040E+04	.75141990E-02
N=	101	LAYER= 1	.50000000E+01	.24392000E+02	.85853630E+02	.29513390E+01	.34672880E+03	.34100040E+04	.76623210E-02
N=	102	LAYER= 1	.50500000E+01	.24775000E+02	.85773370E+02	.29501340E+01	.34688830E+03	.34100040E+04	.78091500E-02
N=	103	LAYER= 1	.51000000E+01	.25165000E+02	.85691940E+02	.29940870E+01	.34705000E+03	.34100040E+04	.79582070E-02
N=	104	LAYER= 1	.51500000E+01	.25560000E+02	.85609190E+02	.30311680E+01	.34721160E+03	.34100040E+04	.81071540E-02
N=	105	LAYER= 1	.52000000E+01	.25959000E+02	.85525650E+02	.31172150E+01	.34737670E+03	.34100040E+04	.82594940E-02
N=	106	LAYER= 1	.52500000E+01	.26378000E+02	.85438100E+02	.31723160E+01	.34754910E+03	.34100040E+04	.84187390E-02
N=	107	LAYER= 1	.53000000E+01	.26792000E+02	.85351450E+02	.31699190E+01	.34772130E+03	.34100040E+04	.85778470E-02
N=	108	LAYER= 1	.53500000E+01	.27211000E+02	.85263950E+02	.32083670E+01	.34789320E+03	.34100040E+04	.87368230E-02
N=	109	LAYER= 1	.54000000E+01	.27636000E+02	.85175090E+02	.32540940E+01	.34806610E+03	.34100040E+04	.88968350E-02
N=	110	LAYER= 1	.54500000E+01	.28067000E+02	.85084990E+02	.33510800E+01	.34824370E+03	.34100040E+04	.90613700E-02
N=	111	LAYER= 1	.55000000E+01	.28519000E+02	.84990710E+02	.34023830E+01	.34842990E+03	.34100040E+04	.92339230E-02
N=	112	LAYER= 1	.55500000E+01	.28964000E+02	.84897680E+02	.33999560E+01	.34861200E+03	.34100040E+04	.94028190E-02
N=	113	LAYER= 1	.56000000E+01	.29416000E+02	.84803440E+02	.34998930E+01	.34879380E+03	.34100040E+04	.95715680E-02
N=	114	LAYER= 1	.56500000E+01	.29889000E+02	.84704800E+02	.35545230E+01	.34898900E+03	.34100040E+04	.97529460E-02
N=	115	LAYER= 1	.57000000E+01	.30355000E+02	.84607440E+02	.35484050E+01	.34917880E+03	.34100040E+04	.99295080E-02
N=	116	LAYER= 1	.57500000E+01	.30827000E+02	.84509040E+02	.35957050E+01	.34936830E+03	.34100040E+04	.10105910E-01

N=	117 LAYER= 1	.58000000E+01	.31307000E+02	.84408960E+02	.36432420E+01	.34956250E+03	.34100030E+04	.10286770E-01
N=	118 LAYER= 1	.58500000E+01	.31792000E+02	.84307820E+02	.37524660E+01	.34976130E+03	.34100030E+04	.10472080E-01
N=	119 LAYER= 1	.59000010E+01	.32302000E+02	.84201580E+02	.38109210E+01	.34996460E+03	.34100040E+04	.10661840E-01
N=	120 LAYER= 1	.59500000E+01	.32804000E+02	.84097100E+02	.38042160E+01	.35016770E+03	.34100030E+04	.10851410E-01
N=	121 LAYER= 1	.60000000E+01	.33313000E+02	.83991110E+02	.38576810E+01	.35037390E+03	.34100040E+04	.11044240E-01
N=	122 LAYER= 1	.60500000E+01	.33830000E+02	.83883540E+02	.39078450E+01	.35058220E+03	.34100030E+04	.11239180E-01
N=	123 LAYER= 1	.61000000E+01	.34353000E+02	.83774650E+02	.40242700E+01	.35079020E+03	.34100030E+04	.11433920E-01
N=	124 LAYER= 1	.61500000E+01	.34902000E+02	.83660490E+02	.40882850E+01	.35101120E+03	.34100030E+04	.11641110E-01
N=	125 LAYER= 1	.62000000E+01	.35443000E+02	.83547910E+02	.40857890E+01	.35122560E+03	.34100030E+04	.11842320E-01
N=	126 LAYER= 1	.62500000E+01	.35992000E+02	.83433760E+02	.42049710E+01	.35144570E+03	.34100030E+04	.12049050E-01
N=	127 LAYER= 1	.63000000E+01	.36567000E+02	.83314420E+02	.42640450E+01	.35167270E+03	.34100030E+04	.12262440E-01
N=	128 LAYER= 1	.63500000E+01	.37133000E+02	.83196830E+02	.42613320E+01	.35189800E+03	.34100030E+04	.12474430E-01
N=	129 LAYER= 1	.64000000E+01	.37708000E+02	.83077490E+02	.43211920E+01	.35212760E+03	.34100030E+04	.12690750E-01
N=	130 LAYER= 1	.64500000E+01	.38291000E+02	.82956410E+02	.43798760E+01	.35235790E+03	.34100030E+04	.12907960E-01
N=	131 LAYER= 1	.65000000E+01	.38883000E+02	.82833650E+02	.44428080E+01	.35259010E+03	.34100030E+04	.13127200E-01
N=	132 LAYER= 1	.65500000E+01	.39484000E+02	.82708910E+02	.45081520E+01	.35282670E+03	.34100030E+04	.13350730E-01
N=	133 LAYER= 1	.66000000E+01	.40094000E+02	.82582340E+02	.45680660E+01	.35306870E+03	.34100030E+04	.13579680E-01
N=	134 LAYER= 1	.66500000E+01	.40713000E+02	.82454080E+02	.46488860E+01	.35330890E+03	.34100030E+04	.13807220E-01
N=	135 LAYER= 1	.66999990E+01	.41347000E+02	.82322820E+02	.47142170E+01	.35355940E+03	.34100030E+04	.14044690E-01
N=	136 LAYER= 1	.67500000E+01	.41985000E+02	.82190730E+02	.47643390E+01	.35380680E+03	.34100030E+04	.14279590E-01
N=	137 LAYER= 1	.68000000E+01	.42633000E+02	.82056490E+02	.48293570E+01	.35405840E+03	.34100030E+04	.14518710E-01
N=	138 LAYER= 1	.68500000E+01	.43290000E+02	.81920570E+02	.49149870E+01	.35431420E+03	.34100030E+04	.14762050E-01
N=	139 LAYER= 1	.69000000E+01	.43963000E+02	.81781340E+02	.49873720E+01	.35457520E+03	.34100030E+04	.15010700E-01
N=	140 LAYER= 1	.69500000E+01	.44641000E+02	.81641170E+02	.50360900E+01	.35483910E+03	.34100030E+04	.15262400E-01
N=	141 LAYER= 1	.70000000E+01	.45329000E+02	.81498990E+02	.51069160E+01	.35510360E+03	.34100030E+04	.15514880E-01
N=	142 LAYER= 1	.70500000E+01	.46028000E+02	.81354640E+02	.51960920E+01	.35537200E+03	.34100030E+04	.15771500E-01
N=	143 LAYER= 1	.71000000E+01	.46742000E+02	.81207240E+02	.52695470E+01	.35564790E+03	.34100030E+04	.16035610E-01
N=	144 LAYER= 1	.71500000E+01	.47462000E+02	.81058530E+02	.53252530E+01	.35592300E+03	.34100030E+04	.16299340E-01
N=	145 LAYER= 1	.71999990E+01	.48193000E+02	.80907770E+02	.54014050E+01	.35620320E+03	.34100030E+04	.16568290E-01
N=	146 LAYER= 1	.72500000E+01	.48936000E+02	.80754540E+02	.54972780E+01	.35648620E+03	.34100030E+04	.16840200E-01
N=	147 LAYER= 1	.73000000E+01	.49695000E+02	.80598140E+02	.55699060E+01	.35677530E+03	.34100020E+04	.17118390E-01
N=	148 LAYER= 1	.73500000E+01	.50460000E+02	.80440560E+02	.56297520E+01	.35706360E+03	.34100020E+04	.17396160E-01
N=	149 LAYER= 1	.74000000E+01	.51237000E+02	.80280530E+02	.57068830E+01	.35735680E+03	.34100020E+04	.17679050E-01
N=	150 LAYER= 1	.74500000E+01	.52025000E+02	.80118330E+02	.58081520E+01	.35765370E+03	.34100020E+04	.17965950E-01
N=	151 LAYER= 1	.75000000E+01	.52832000E+02	.79952320E+02	.58894850E+01	.35795770E+03	.34100020E+04	.18260170E-01
N=	152 LAYER= 1	.75500000E+01	.53645000E+02	.79785240E+02	.59512560E+01	.35826430E+03	.34100020E+04	.18557220E-01
N=	153 LAYER= 1	.76000000E+01	.54471000E+02	.79615440E+02	.60347270E+01	.35857220E+03	.34100020E+04	.18855980E-01
N=	154 LAYER= 1	.76500000E+01	.55309000E+02	.79443340E+02	.61143190E+01	.35888360E+03	.34100020E+04	.19158670E-01
N=	155 LAYER= 1	.77000000E+01	.56160000E+02	.79268740E+02	.62040410E+01	.35919980E+03	.34100020E+04	.19466350E-01
N=	156 LAYER= 1	.77500000E+01	.57025000E+02	.79091250E+02	.62905820E+01	.35952040E+03	.34100020E+04	.19778990E-01

N=	157 LAYER= 1	.78000000E+01	.57902000E+02	.78911400E+02	.63791210E+01	.35984680E+03	.34100020E+04	.20097650E-01
N=	158 LAYER= 1	.78500000E+01	.58794000E+02	.78728550E+02	.64698920E+01	.36017430E+03	.34100020E+04	.20417940E-01
N=	159 LAYER= 1	.79000000E+01	.59699000E+02	.78543210E+02	.65568560E+01	.36050630E+03	.34100020E+04	.20743130E-01
N=	160 LAYER= 1	.79500000E+01	.60618000E+02	.78355080E+02	.66517320E+01	.36084280E+03	.34100020E+04	.21073190E-01
N=	161 LAYER= 1	.80000010E+01	.61552000E+02	.78163980E+02	.67421010E+01	.36118470E+03	.34100020E+04	[illegible]
N=	162 LAYER= 1	.80500000E+01	.62499000E+02	.77970320E+02	.68347960E+01	.36152980E+03	.34100020E+04	.21748840E-01
N=	163 LAYER= 1	.81000000E+01	.63462000E+02	.77773570E+02	.69342600E+01	.36187690E+03	.34100020E+04	.22091130E-01
N=	164 LAYER= 1	.81500000E+01	.64440000E+02	.77573840E+02	.70307510E+01	.36223050E+03	.34100020E+04	.22440310E-01
N=	165 LAYER= 1	.82000000E+01	.65433000E+02	.77371180E+02	.71273880E+01	.36258810E+03	.34100020E+04	.22794190E-01
N=	166 LAYER= 1	.82500000E+01	.66441000E+02	.77165530E+02	.72245860E+01	.36294980E+03	.34100020E+04	.23152760E-01
N=	167 LAYER= 1	.83000000E+01	.67465000E+02	.76956880E+02	.73298000E+01	.36331670E+03	.34100020E+04	.23517050E-01
N=	168 LAYER= 1	.83499990E+01	.68506000E+02	.76744770E+02	.74324850E+01	.36368750E+03	.34100020E+04	.23885970E-01
N=	169 LAYER= 1	.84000000E+01	.69562000E+02	.76529790E+02	.75327790E+01	.36406330E+03	.34100020E+04	.24260530E-01
N=	170 LAYER= 1	.84500000E+01	.70635000E+02	.76311460E+02	.76428780E+01	.36444290E+03	.34100020E+04	.24639640E-01
N=	171 LAYER= 1	.85000010E+01	.71726000E+02	.76089690E+02	.77491960E+01	.36482730E+03	.34100020E+04	.25024290E-01
N=	172 LAYER= 1	.85500000E+01	.72833000E+02	.75864780E+02	.78554750E+01	.36521770E+03	.34100020E+04	.25415560E-01
N=	173 LAYER= 1	.86000000E+01	.73958000E+02	.75636400E+02	.79643300E+01	.36561160E+03	.34100020E+04	.25811250E-01
N=	174 LAYER= 1	.86500000E+01	.75100000E+02	.75404710E+02	.80762490E+01	.36601010E+03	.34100020E+04	.26212400E-01
N=	175 LAYER= 1	.87000000E+01	.76261000E+02	.75169360E+02	.81913380E+01	.36641210E+03	.34100020E+04	.26617880E-01
N=	176 LAYER= 1	.87500000E+01	.77440000E+02	.74930490E+02	.83061090E+01	.36681960E+03	.34100020E+04	.27029770E-01
N=	177 LAYER= 1	.88000000E+01	.78638000E+02	.74687950E+02	.84233430E+01	.36723250E+03	.34100020E+04	.27448040E-01
N=	178 LAYER= 1	.88500000E+01	.79855000E+02	.74441740E+02	.85430240E+01	.36765190E+03	.34100020E+04	.27873690E-01
N=	179 LAYER= 1	.89000000E+01	.81092000E+02	.74191700E+02	.86607440E+01	.36807430E+03	.34100020E+04	.28303500E-01
N=	180 LAYER= 1	.89500000E+01	.82348000E+02	.73938070E+02	.87795700E+01	.36850100E+03	.34100020E+04	.28738490E-01
N=	181 LAYER= 1	.90000010E+01	.83624000E+02	.73680520E+02	.89050110E+01	.36893370E+03	.34100020E+04	.29180670E-01
N=	182 LAYER= 1	.90500000E+01	.84921000E+02	.73418980E+02	.90321460E+01	.36937240E+03	.34100020E+04	.29630020E-01
N=	183 LAYER= 1	.91000000E+01	.86239000E+02	.73153400E+02	.91592280E+01	.36981390E+03	.34100020E+04	.30083360E-01
N=	184 LAYER= 1	.91500010E+01	.87578000E+02	.72883800E+02	.92872640E+01	.37026320E+03	.34100020E+04	.30545760E-01
N=	185 LAYER= 1	.92000000E+01	.88939000E+02	.72610080E+02	.94194550E+01	.37071720E+03	.34100020E+04	.31014090E-01
N=	186 LAYER= 1	.92500010E+01	.90322000E+02	.72332080E+02	.95544010E+01	.37117570E+03	.34100020E+04	.31488290E-01
N=	187 LAYER= 1	.93000000E+01	.91728000E+02	.72049750E+02	.96880340E+01	.37163960E+03	.34100020E+04	.31969300E-01
N=	188 LAYER= 1	.93500000E+01	.93156000E+02	.71763210E+02	.98206620E+01	.37210900E+03	.34100020E+04	.32457190E-01
N=	189 LAYER= 1	.94000000E+01	.94607000E+02	.71472370E+02	.99619060E+01	.37258160E+03	.34100020E+04	.32949650E-01
N=	190 LAYER= 1	.94500000E+01	.96083000E+02	.71176770E+02	.10104370E+02	.37306320E+03	.34100020E+04	.33452830E-01
N=	191 LAYER= 1	.94999990E+01	.97582000E+02	.70876780E+02	.10244220E+02	.37354880E+03	.34100020E+04	.33961610E-01
N=	192 LAYER= 1	.95500010E+01	.99106000E+02	.70572140E+02	.10406480E+02	.37404020E+03	.34100020E+04	.34477840E-01
N=	193 LAYER= 1	.96000000E+01	.10066000E+03	.70261760E+02	.10537850E+02	.37453820E+03	.34100020E+04	.35002480E-01
N=	194 LAYER= 1	.96500010E+01	.10223000E+03	.69948550E+02	.10668750E+02	.37503710E+03	.34100020E+04	.35529450E-01
N=	195 LAYER= 1	.97000000E+01	.10383000E+03	.69629590E+02	.10846020E+02	.37554610E+03	.34100020E+04	.36068710E-01
N=	196 LAYER= 1	.97500010E+01	.10546000E+03	.69304990E+02	.10986600E+02	.37606120E+03	.34100020E+04	.36616050E-01

N=	197	LAYER= 1	.98000000E+01	.10711000E+03	.68976780E+02	.11161380E+02	.37657880E+03	.34100020E+04	.37167560E-01
N=	198	LAYER= 1	.98500000E+01	.10880000E+03	.68640890E+02	.11334440E+02	.37710680E+03	.34100020E+04	.37731990E-01
N=	199	LAYER= 1	.99000000E+01	.11051000E+03	.68301450E+02	.11472120E+02	.37763690E+03	.34100020E+04	.38300350E-01
N=	200	LAYER= 1	.99500000E+01	.11225000E+03	.67956390E+02	.11609890E+02	.37817350E+03	.34100020E+04	.38877520E-01
N=	201	LAYER= 1	.99999990E+01	.11401000E+03	.67607740E+02	.11778910E+02	.37871560E+03	.34100020E+04	.39462290E-01
N=	202	LAYER= 1	.10050000E+02	.11581000E+03	.67251570E+02	.11980020E+02	.37926370E+03	.34100020E+04	.40055580E-01
N=	203	LAYER= 1	.10100000E+02	.11764000E+03	.66889850E+02	.12146750E+02	.37982040E+03	.34100020E+04	.40660200E-01
N=	204	LAYER= 1	.10150000E+02	.11950000E+03	.66522620E+02	.12312220E+02	.38038030E+03	.34100020E+04	.41270270E-01
N=	205	LAYFR= 1	.10200000E+02	.12139000E+03	.66149890E+02	.12509020E+02	.38094850E+03	.34100020E+04	.41891480E-01
N=	206	LAYER= 1	.10250000E+02	.12332000E+03	.65769710E+02	.12671130E+02	.38152290E+03	.34100010E+04	.42521690E-01
N=	207	LAYER= 1	.10300000E+02	.12527000E+03	.65386060E+02	.12831710E+02	.38210080E+03	.34100020E+04	.43157890E-01
N=	208	LAYER= 1	.10350000E+02	.12726000E+03	.64995030E+02	.13056350E+02	.38268620E+03	.34100010E+04	.43804810E-01
N=	209	LAYER= 1	.10400000E+02	.12929000E+03	.64596620E+02	.13247180E+02	.38327990E+03	.34100020E+04	.44463280E-01
N=	210	LAYER= 1	.10450000E+02	.13135000E+03	.64192810E+02	.13403490E+02	.38387820E+03	.34100020E+04	.45129220E-01
N=	211	LAYER= 1	.10500000E+02	.13344000E+03	.63783660E+02	.13622810E+02	.38448250E+03	.34100020E+04	.45804430E-01
N=	212	LAYER= 1	.10550000E+02	.13558000E+03	.63365250E+02	.13808740E+02	.38509600E+03	.34100020E+04	.46492550E-01
N=	213	LAYER= 1	.10600000E+02	.13774000E+03	.62943470E+02	.13992030E+02	.38571010E+03	.34100010E+04	.47184110E-01
N=	214	LAYER= 1	.10650000E+02	.13995000E+03	.62512550E+02	.14237540E+02	.38633520E+03	.34100020E+04	.47890950E-01
N=	215	LAYER= 1	.10700000E+02	.14220000E+03	.62074390E+02	.14418360E+02	.38696800E+03	.34100020E+04	.48609170E-01
N=	216	LAYER= 1	.10750000E+02	.14448000E+03	.61630990E+02	.14628260E+02	.38760380E+03	.34100010E+04	.49334050E-01
N=	217	LAYER= 1	.10800000E+02	.14681000E+03	.61178530E+02	.14867900E+02	.38824830E+03	.34100010E+04	.50071720E-01
N=	218	LAYER= 1	.10850000E+02	.14918000E+03	.60718940E+02	.15074390E+02	.38889860E+03	.34100020E+04	.50819480E-01
N=	219	LAYER= 1	.10900000E+02	.15159000E+03	.60252280E+02	.15278360E+02	.38955670E+03	.34100020E+04	.51579490E-01
N=	220	LAYER= 1	.10950000E+02	.15404000E+03	.59778570E+02	.15479970E+02	.39021860E+03	.34100020E+04	.52347300E-01
N=	221	LAYER= 1	.11000000E+02	.15653000E+03	.59297870E+02	.15742260E+02	.39088700E+03	.34100020E+04	.53126160E-01
N=	222	LAYER= 1	.11050000E+02	.15908000E+03	.58806320E+02	.15971430E+02	.39156700E+03	.34100020E+04	.53922330E-01
N=	223	LAYER= 1	.11100000E+02	.16166000E+03	.58309750E+02	.16197830E+02	.39224900E+03	.34100010E+04	.54724560E-01
N=	224	LAYER= 1	.11150000E+02	.16430000E+03	.57802460E+02	.16453060E+02	.39293960E+03	.34100020E+04	.55540850E-01
N=	225	LAYER= 1	.11200000E+02	.16698000E+03	.57288280E+02	.16674540E+02	.39363600E+03	.34100020E+04	.56368150E-01
N=	226	LAYER= 1	.11250000E+02	.16971000E+03	.56765380E+02	.16954680E+02	.39434110E+03	.34100020E+04	.57209750E-01
N=	227	LAYER= 1	.11300000E+02	.17250000E+03	.56231890E+02	.17202050E+02	.39505320E+03	.34100010E+04	.58064340E-01
N=	228	LAYER= 1	.11350000E+02	.17533000E+03	.55691660E+02	.17416240E+02	.39577010E+03	.34100010E+04	.58929110E-01
N=	229	LAYER= 1	.11400000E+02	.17821000E+03	.55142830E+02	.17688560E+02	.39649280E+03	.34100010E+04	.59805590E-01
N=	230	LAYER= 1	.11450000E+02	.18115000E+03	.54583550E+02	.17988300E+02	.39722500E+03	.34100010E+04	.60698390E-01
N=	231	LAYER= 1	.11500000E+02	.18415000E+03	.54013860E+02	.18254460E+02	.39796490E+03	.34100010E+04	.61605530E-01
N=	232	LAYER= 1	.11550000E+02	.18720000E+03	.53435740E+02	.18517140E+02	.39870920E+03	.34100020E+04	.62523420E-01
N=	233	LAYER= 1	.11600000E+02	.19031000E+03	.52847350E+02	.18777490E+02	.39946150E+03	.34100010E+04	.63456570E-01
N=	234	LAYER= 1	.11650000E+02	.19347000E+03	.52250600E+02	.19064460E+02	.40021900E+03	.34100010E+04	.64401600E-01
N=	235	LAYER= 1	.11700000E+02	.19670000E+03	.51641820E+02	.19377540E+02	.40098460E+03	.34100010E+04	.65362680E-01
N=	236	LAYER= 1	.11750000E+02	.19999000E+03	.51022930E+02	.19657200E+02	.40175790E+03	.34100010E+04	.66339450E-01

N=	237	LAYER= 1	.11800000E+02	.20334000E+03	.50394010E+02	.19963180E+02	.40253600E+03	.34100010E+04	.67328360E-01
N=	238	LAYER= 1	.11850000E+02	.20676000E+03	.49753250E+02	.20265810E+02	.40332330E+03	.34100010E+04	.68335510E-01
N=	239	LAYER= 1	.11900000E+02	.21024000E+03	.49102580E+02	.20563980E+02	.40411520E+03	.34100010E+04	.69355160E-01
N=	240	LAYER= 1	.11950000E+02	.21379000E+03	.48440240E+02	.20887870E+02	.40491420E+03	.34100010E+04	.70390900E-01
N=	241	LAYER= 1	.12000000E+02	.21741000E+03	.47766250E+02	.21207490E+02	.40572070E+03	.34100010E+04	.71443750E-01
N=	242	LAYER= 1	.12050000E+02	.22110000E+03	.47080750E+02	.21523170E+02	.40653340E+03	.34100010E+04	.72512020E-01
N=	243	LAYER= 1	.12100000E+02	.22486000E+03	.46383770E+02	.21863620E+02	.40735210E+03	.34100010E+04	.73595930E-01
N=	244	LAYER= 1	.12150000E+02	.22870000E+03	.45673580E+02	.22199050E+02	.40817900E+03	.34100010E+04	.74698870E-01
N=	245	LAYER= 1	.12200000E+02	.23261000E+03	.44952110E+02	.22559020E+02	.40901020E+03	.34100010E+04	.75815900E-01
N=	246	LAYER= 1	.12250000E+02	.23661000E+03	.44215740E+02	.22914030E+02	.40985120E+03	.34100010E+04	.76954800E-01
N=	247	LAYER= 1	.12300000E+02	.24068000E+03	.43468280E+02	.23235320E+02	.41069560E+03	.34100010E+04	.78107580E-01
N=	248	LAYER= 1	.12350000E+02	.24483000E+03	.42707990E+02	.23608680E+02	.41154580E+03	.34100010E+04	.79277410E-01
N=	249	LAYER= 1	.12400000E+02	.24907000E+03	.41933130E+02	.24005170E+02	.41240410E+03	.34100010E+04	.80468070E-01
N=	250	LAYER= 1	.12450000E+02	.25340000E+03	.41143820E+02	.24395840E+02	.41326890E+03	.34100010E+04	.81678180E-01
N=	251	LAYER= 1	.12500000E+02	.25782000E+03	.40340170E+02	.24752910E+02	.41414060E+03	.34100010E+04	.82908510E-01
N=	252	LAYER= 1	.12550000E+02	.26232000E+03	.39524130E+02	.25132350E+02	.41501530E+03	.34100010E+04	.84154140E-01
N=	253	LAYER= 1	.12600000E+02	.26692000E+03	.38692180E+02	.25561070E+02	.41589660E+03	.34100010E+04	.85420620E-01
N=	254	LAYER= 1	.12650000E+02	.27162000E+03	.37844470E+02	.25956220E+02	.41678520E+03	.34100010E+04	.86709540E-01
N=	255	LAYER= 1	.12700000E+02	.27641000E+03	.36982920E+02	.26372500E+02	.41767800E+03	.34100010E+04	.88017010E-01
N=	256	LAYER= 1	.12750000E+02	.28131000E+03	.36104080E+02	.26809290E+02	.41857720E+03	.34100010E+04	.89347030E-01
N=	257	LAYER= 1	.12800000E+02	.28631000E+03	.35209890E+02	.27211970E+02	.41948130E+03	.34100010E+04	.90697680E-01
N=	258	LAYER= 1	.12850000E+02	.29141000E+03	.34300520E+02	.27661740E+02	.42038960E+03	.34100010E+04	.92068630E-01
N=	259	LAYER= 1	.12900000E+02	.29663000E+03	.33372530E+02	.28131650E+02	.42130430E+03	.34100010E+04	.93464140E-01
N=	260	LAYER= 1	.12950000E+02	.30196000E+03	.32427900E+02	.28567350E+02	.42222300E+03	.34100010E+04	.94881120E-01
N=	261	LAYER= 1	.13000000E+02	.30740000E+03	.31466780E+02	.29047940E+02	.42314570E+03	.34100010E+04	.96320330E-01
N=	262	LAYER= 1	.13050000E+02	.31297000E+03	.30485830E+02	.29520700E+02	.42407490E+03	.34100010E+04	.97786470E-01
N=	263	LAYER= 1	.13100000E+02	.31865000E+03	.29488770E+02	.29621730E+02	.42500580E+03	.34100010E+04	.99272810E-01
N=	264	LAYER= 1	.13150000E+02	.32432000E+03	.28496720E+02	.30779220E+02	.39622580E+03	.34100010E+04	.10078440E+00
N=	265	LAYER= 1	.13200000E+02	.32968000E+03	.27561890E+02	.31017610E+02	.37560240E+03	.34100010E+04	.10232150E+00
N=	266	LAYER= 1	.13250000E+02	.33489000E+03	.26655980E+02	.31415540E+02	.36133250E+03	.34100010E+04	.10387930E+00
N=	267	LAYER= 1	.13300000E+02	.34001000E+03	.25768370E+02	.31868640E+02	.34964270E+03	.34100010E+04	.10546030E+00
N=	268	LAYER= 1	.13350000E+02	.34506000E+03	.24895450E+02	.32280860E+02	.33944130E+03	.34100010E+04	.10706440E+00
N=	269	LAYER= 1	.13400000E+02	.35004000E+03	.24037100E+02	.32654810E+02	.33025490E+03	.34100010E+04	.10868690E+00
N=	270	LAYER= 1	.13450000E+02	.35496000E+03	.23191490E+02	.33080890E+02	.32179730E+03	.34100010E+04	.11032860E+00
N=	271	LAYER= 1	.13500000E+02	.35984000E+03	.22355110E+02	.33511910E+02	.31387120E+03	.34100010E+04	.11199430E+00
N=	272	LAYER= 1	.13550000E+02	.36467000E+03	.21529590E+02	.33919010E+02	.30638180E+03	.34100010E+04	.11367980E+00
N=	273	LAYER= 1	.13600000E+02	.36946000E+03	.20713160E+02	.34345680E+02	.29924010E+03	.34100010E+04	.11538650E+00
N=	274	LAYER= 1	.13650000E+02	.37421000E+03	.19905740E+02	.34724730E+02	.29238680E+03	.34100010E+04	.11711430E+00
N=	275	LAYER= 1	.13700000E+02	.37891000E+03	.19108960E+02	.35093520E+02	.28579280E+03	.34100010E+04	.11885840E+00
N=	276	LAYER= 1	.13750000E+02	.38357000E+03	.18321060E+02	.35495610E+02	.27940430E+03	.34100010E+04	.12062340E+00

N=	277	LAYER=	1	.13800000E+02	.38819000E+03	.17541980E+02	.35933800E+02	.27319680E+03	.34100010E+04	.12240830E+00
N=	278	LAYER=	1	.13850000E+02	.39278000E+03	.16769980E+02	.36319480E+02	.26958920E+03	.34100010E+04	.12421180E+00
N=	279	LAYER=	1	.13900000E+02	.39740000E+03	.15994960E+02	.36680230E+02	.26797530E+03	.34100010E+04	.12603720E+00
N=	280	LAYER=	1	.13950000E+02	.40205000E+03	.15216950E+02	.37039690E+02	.26638870E+03	.34100010E+04	.12787960E+00
N=	281	LAYER=	1	.14000000E+02	.40673000E+03	.14435960E+02	.37439000E+02	.26482370E+03	.34100010E+04	.12974130E+00
N=	282	LAYER=	1	.14050000E+02	.41145000E+03	.13650400E+02	.37839300E+02	.26327580E+03	.34100010E+04	.13162410E+00
N=	283	LAYER=	1	.14100000E+02	.41620000E+03	.12861950E+02	.38239480E+02	.26174500E+03	.34100010E+04	.13352510E+00
N=	284	LAYER=	1	.14150000E+02	.42099000E+03	.12068990E+02	.38640850E+02	.26022600E+03	.34100010E+04	.13544790E+00
N=	285	LAYER=	1	.14200000E+02	.42581000E+03	.11273210E+02	.39043270E+02	.25871960E+03	.34100010E+04	.13738900E+00
N=	286	LAYER=	1	.14250000E+02	.43067000E+03	.10473000E+02	.39447020E+02	.25722090E+03	.34100010E+04	.13935240E+00
N=	287	LAYER=	1	.14300000E+02	.43556000E+03	.96700520E+01	.39852140E+02	.25573220E+03	.34100010E+04	.14133340E+00
N=	288	LAYER=	1	.14350000E+02	.44049000E+03	.88627500E+01	.40259730E+02	.25424800E+03	.34100010E+04	.14333730E+00
N=	289	LAYER=	1	.14400000E+02	.44545000E+03	.80527780E+01	.40668610E+02	.25277060E+03	.34100010E+04	.14535950E+00
N=	290	LAYER=	1	.14450000E+02	.45045000E+03	.72385450E+01	.41120410E+02	.25129530E+03	.34100010E+04	.14740460E+00
N=	291	LAYER=	1	.14500000E+02	.45549000E+03	.64200890E+01	.39773280E+02	.24982180E+03	.34100010E+04	.14947210E+00
N=	292	LAYER=	1	.14550000E+02	.46013000E+03	.56686030E+01	.42727880E+02	.20680570E+03	.34100010E+04	.15155420E+00
N=	293	LAYER=	1	.14600000E+02	.46412000E+03	.50239490E+01	.42371720E+02	.18323230E+03	.34100010E+04	.15365480E+00
N=	294	LAYER=	1	.14650000E+02	.46773000E+03	.44419170E+01	.42624510E+02	.16551100E+03	.34100010E+04	.15577110E+00
N=	295	LAYER=	1	.14700000E+02	.47104000E+03	.39092740E+01	.42864520E+02	.15051290E+03	.34100010E+04	.15790720E+00
N=	296	LAYER=	1	.14750000E+02	.47407000E+03	.34225430E+01	.43001320E+02	.13726140E+03	.34100010E+04	.16004990E+00
N=	297	LAYER=	1	.14800000E+02	.47685000E+03	.29766960E+01	.43258920E+02	.12521230E+03	.34100010E+04	.16220190E+00
N=	298	LAYER=	1	.14850000E+02	.47941000E+03	.25667320E+01	.43530740E+02	.11401740E+03	.34100010E+04	.16437230E+00
N=	299	LAYER=	1	.14900000E+02	.48175000E+03	.21925030E+01	.43671470E+02	.10354230E+03	.34100010E+04	.16655060E+00
N=	300	LAYER=	1	.14950000E+02	.48388000E+03	.18522840E+01	.43799410E+02	.93659210E+02	.34100010E+04	.16873530E+00
N=	301	LAYER=	1	.15000000E+02	.48581000E+03	.15443560E+01	.43956940E+02	.84268760E+02	.34100010E+04	.17092700E+00
N=	302	LAYER=	1	.15050000E+02	.48755000E+03	.12670240E+01	.44063630E+02	.75288480E+02	.34100010E+04	.17312820E+00
N=	303	LAYER=	1	.15100000E+02	.48910000E+03	.10201880E+01	.44257190E+02	.66699160E+02	.34100010E+04	.17532960E+00
N=	304	LAYER=	1	.15150000E+02	.49048000E+03	.80061580E+00	.44323400E+02	.58373280E+02	.34100010E+04	.17755320E+00
N=	305	LAYER=	1	.15200000E+02	.49167000E+03	.61139610E+00	.44282680E+02	.50436810E+02	.34100010E+04	.17975510E+00
N=	306	LAYER=	1	.15250000E+02	.49270000E+03	.44772810E+00	.44509340E+02	.42695030E+02	.34100010E+04	.18198070E+00
N=	307	LAYER=	1	.15300000E+02	.49356000E+03	.31114570E+00	.44506580E+02	.35227210E+02	.34100010E+04	.18420050E+00
N=	308	LAYER=	1	.15350000E+02	.49426000E+03	.20001010E+00	.44548020E+02	.27964380E+02	.34100010E+04	.18642850E+00
N=	309	LAYER=	1	.15400000E+02	.49480000E+03	.11431690E+00	.44115040E+02	.20943780E+02	.34100010E+04	.18864740E+00
N=	310	LAYER=	1	.15450000E+02	.49518000E+03	.54028930E-01	.42912730E+02	.14273500E+02	.34100010E+04	.19081540E+00
N=	311	LAYER=	1	.15500000E+02	.49541000E+03	.17538510E-01	.39799420E+02	.80724710E+01	.34100010E+04	.19288380E+00
N=	311	LAYER=	1	.15500000E+02	.49541000E+03	.17538510E-01	.39799420E+02	.80724710E+01	.34100010E+04	.19288380E+00

Pressure	Rate	Pressure	Rate	Pressure	Rate
8.000	1.048	172.000	17.158	336.000	31.514
12.000	1.529	176.000	17.480	340.000	31.868
16.000	1.982	180.000	17.871	344.000	32.194
20.000	2.450	184.000	18.241	348.000	32.502
4.000	2.909	188.000	18.584	352.000	32.825
28.000	3.336	192.000	18.931	356.000	33.173
32.000	3.776	196.000	19.310	360.000	33.525
36.000	4.206	200.000	19.658	364.000	33.863
40.000	4.559	204.000	20.022	368.000	34.216
44.000	4.990	208.000	20.372	372.000	34.548
48.000	5.381	212.000	20.725	376.000	34.865
52.000	5.805	216.000	21.083	380.000	35.188
56.000	6.187	220.000	21.429	384.000	35.536
60.000	6.588	224.000	21.786	388.000	35.916
64.000	6.987	228.000	22.138	392.000	36.254
68.000	7.383	232.000	22.503	396.000	36.571
72.000	7.776	236.000	22.860	400.000	36.881
76.000	8.165	240.000	23.182	404.000	37.206
80.000	8.557	244.000	23.534	408.000	37.547
84.000	8.942	248.000	23.905	412.000	37.886
88.000	9.328	252.000	24.270	416.000	38.223
92.000	9.713	256.000	24.606	420.000	38.558
96.000	10.096	260.000	24.937	424.000	38.892
100.000	10.482	264.000	25.289	428.000	39.225
104.000	10.861	268.000	25.652	432.000	39.557
108.000	11.253	272.000	25.989	436.000	39.889
112.000	11.590	276.000	26.337	440.000	40.219
116.000	11.997	280.000	26.693	444.000	40.549
120.000	12.364	284.000	27.026	448.000	40.899
124.000	12.727	288.000	27.361	452.000	40.706
128.000	13.126	292.000	27.715	456.000	40.098
132.000	13.472	296.000	28.075	460.000	42.645
136.000	13.844	300.000	28.407	464.000	42.382
140.000	14.242	304.000	28.748	468.000	42.644
144.000	14.584	308.000	29.099	472.000	42.908
148.000	14.972	312.000	29.438	476.000	43.180
152.000	15.312	316.000	29.575	480.000	43.566
156.000	15.686	320.000	29.897	484.000	43.809
160.000	16.052	324.000	30.714	488.000	44.120
164.000	16.424	328.000	30.943	492.000	44.355
168.000	16.779	332.000	31.195		

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25.	50.	.164721E+00	.901040	.999392
50.	124.	.160656E+00	.907147	.999992
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